The Hydrogeology and Hydraulics of Artesian Springs in Canterbury

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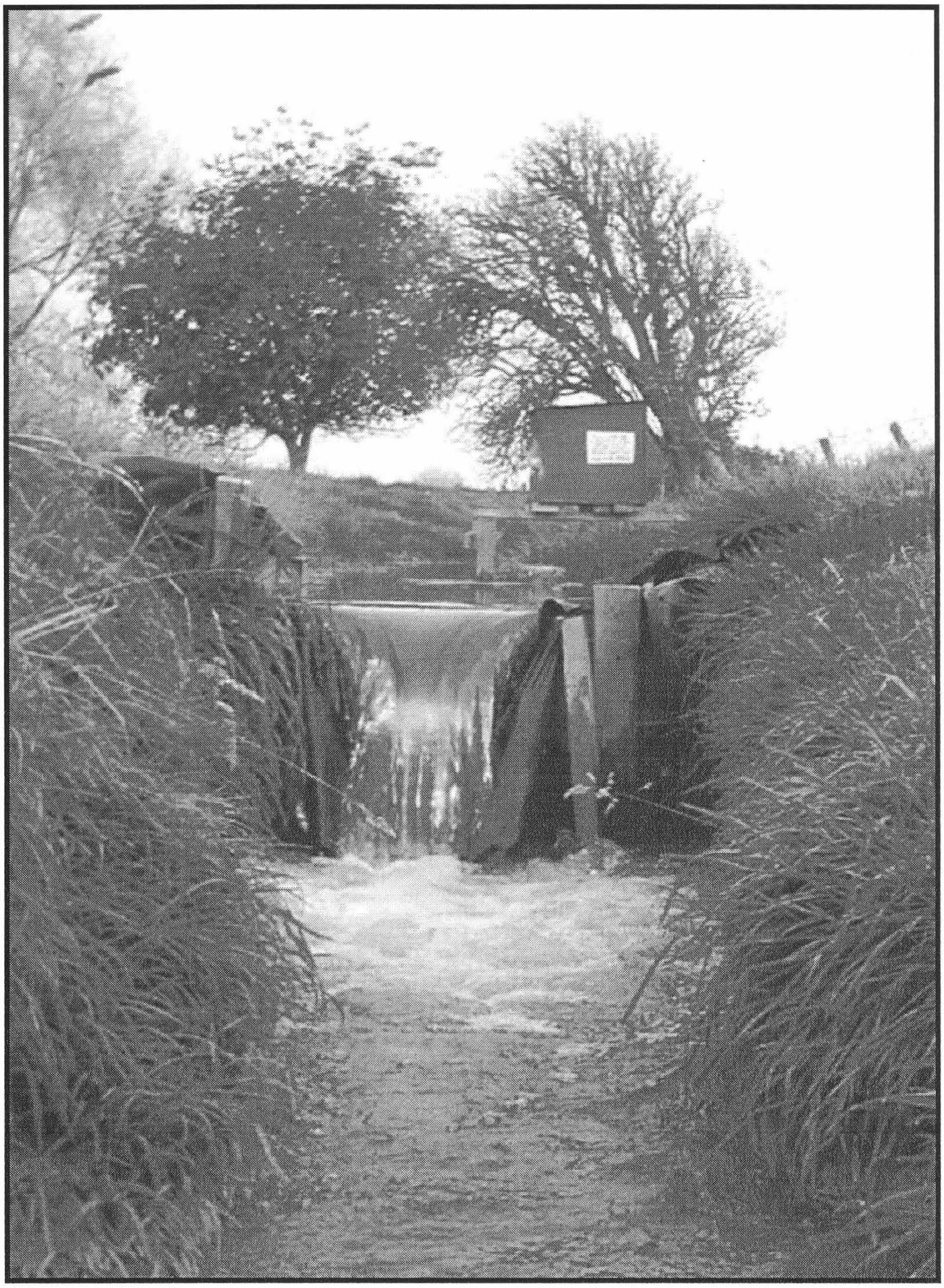
CHRISTCHURCH · NEW ZEALAND

Frontispiece



V-notch weir and water level recorder set up on an artesian fed stream at Brookside, 2002

Abstract

The increasing demand for water in the Canterbury region, and the realisation that spring flow plays an important role in many wetland and river systems, requires methods for predicting changes in spring behaviour as Canterbury's groundwater resources are utilised. This study into the flow of groundwater through artesian spring systems provides a better understanding of the impacts of changes in artesian aquifer pressure.

The aquifer system of the central coastal Canterbury Plains consists of gravels separated by successive layers of fine sediment. The fine sediment acts as a confining aquitard, creating artesian pressures in the gravel aquifers where the piezometric surface is above ground level. Artesian springs occur in the confining aquitard through localised zones of weakness.

Piezometric levels associated with artesian springs in gravel aquifers are not well documented and have never been observed in Canterbury. Examination of near-spring groundwater flow patterns should confirm the shallow artesian aquifer as the main source of water to artesian springs.

Little information is available on the relationship between artesian aquifer pressure and artesian spring discharge. Groundwater flow equations indicate that turbulence occurs in the high velocity flow encountered in artesian spring systems. Energy losses should thus be proportional to velocity squared and the pressure – flow relationship is expected to be non-linear. A non-linear relationship would buffer spring discharge against changes in aquifer pressure induced by groundwater abstraction.

Field investigations were carried out at two spring sites near Christchurch. Near-spring water levels were observed in the aquifer directly below the spring to confirm it as the principal source of water to the spring. Variations in artesian pressure were then induced via groundwater abstraction from nearby wells in the source aquifer, and changes in spring discharge measured.

The upper confined aquifer was confirmed to be the primary source of water for Christchurch's artesian spring systems. The relationship between artesian aquifer pressure and artesian spring discharge was found to be entirely linear for the range of pressures and flows observed. Although theoretical analysis indicates that turbulent flow is occurring at, and close to, the spring vent, the distance over which it occurs is small enough that energy losses due to rapid flow in the groundwater system are negligible. The results imply that any reduction in artesian pressure due to groundwater abstraction will have a direct, linear impact on artesian spring flow.

Acknowledgements

I wish to thank Michael Dicker for the opportunity, and funding, to carry out this project. I would also like to thank the groundwater team at Environment Canterbury. The input and interest of Marc Ettema, Russel Sanders, David Scott and John Weeber was invaluable.

Thanks to Ian Odell, David and Tim Tipple and Susan and Tony McLaughlin, for allowing access to land to set-up and carry out site investigations; without their assistance this project could have never been undertaken.

Finally thanks to my supervisor David Bell.

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1 Introduction

1.1 Project Background

Groundwater and surface water are often treated as separate resources, but very often groundwater is interconnected with lakes and rivers as a part of an ongoing, dynamic relationship. In the case of spring-fed streams, for example, much of the base flow of the stream is dependent on the contribution of springs, which are in turn dependent on groundwater for recharge.

Springs are of value not only because of their water supply potential, but also because of their recreational, ecological, and cultural significance, and reputed medicinal properties. In terms of water supply alone the existence of springs is often paramount for rivers and wetlands, as is the case for many of Christchurch's waterways including the Avon, Heathcote and Halswell river systems. The potential for conflict between the conservation value of springs and utilisation of the water that sustains them means that the understanding of spring hydraulics is an important part of water management.

Drainage of swampy land, which made up much of the Christchurch metropolitan area in pre-European times, has impacted on artesian pressures in the aquifer systems, with some springs now reportedly not flowing or only flowing intermittently. Abstraction of water from shallow aquifers impacts the way in which spring systems that depend upon the aquifer operate. Long-term abstractions will cause a reduction in the volume of water present, resulting in a lowering of the water table or a reduction in water pressure, and in turn a depleted spring discharge rate.

Figures 1-1 and 1-2 show the number of new wells, and in particular shallow wells, drilled in the Canterbury Plains between the Rakaia and Waimakariri Rivers from 1975 to 2002. The number of new wells installed has generally increased annually. Unless the same number of wells are being decommissioned each year, the trend indicates more stress on the aquifer system, which could reach a level that is unsustainable, whereupon mining of the groundwater resource would occur.

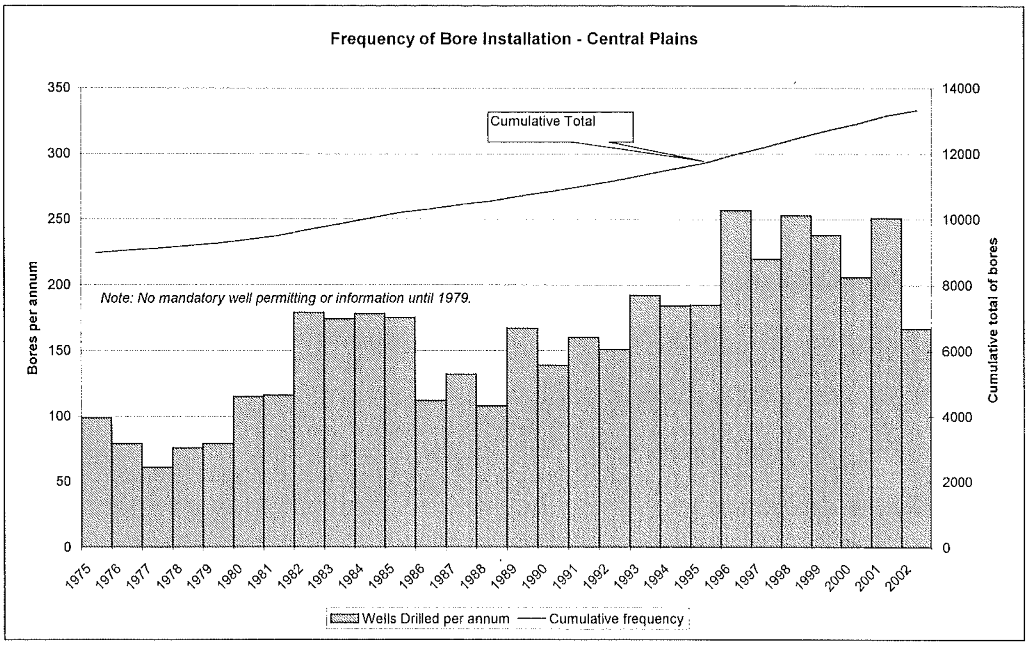


Figure 1-1 Well installation history from Rakaia to Waimakariri Rivers

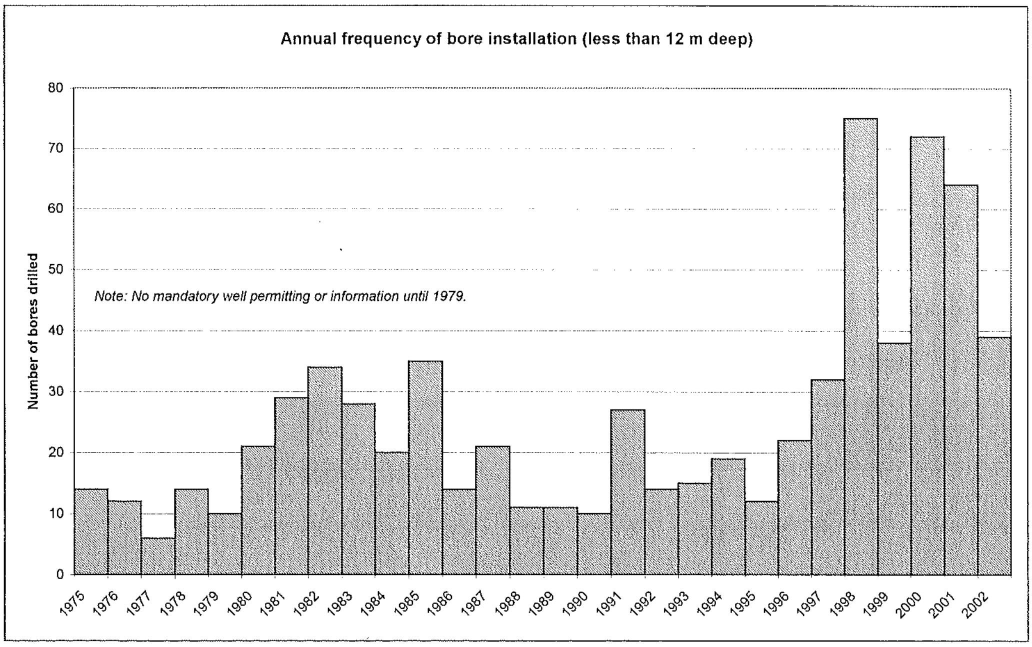


Figure 1-2 Shallow well installation history from Rakaia to Waimakariri Rivers

1.2 Thesis Aims and Objectives

The primary aim of this thesis is to understand the hydraulics and controlling hydrogeology of artesian spring systems in the gravel-based aquifers of the greater Christchurch area. The focus is on near-spring flow mechanisms and direct interference from groundwater abstraction, observing the groundwater flow patterns to an artesian spring, and obtaining a pressure-flow relationship for artesian spring discharge.

Secondary thesis objectives are to determine the applicability of artesian springs as an indicator of aquifer health, i.e. can spring discharge serve as a useful tool to predict stress on the aquifers feeding them, and to derive a methodology for estimating artesian spring depletion due to groundwater abstraction, or to verify that the current method of depletion evaluation is valid.

1.3 Problem Definition

Little literature is available on spring flow, with many groundwater texts simply describing the general conditions required for spring formation. In particular, no mention is made of relationships between groundwater levels and spring discharge, or consequences of changes in aquifer pressure.

Although the concept of stream depletion has been around for many years (Theis 1941, Glover and Balmer 1954, Grigoryev 1957, Hantush 1965, Bochever 1966, Jenkins 1968, Hunt 1999), the application of the resulting models to the special case of artesian spring depletion has not been extensively studied. Current methods of stream depletion are based on assumptions that are not applicable to artesian springs. Unlike a stream interacting with groundwater along its length, most artesian spring systems are restricted to discrete points of inflow to an effectively perched stream with little interaction with groundwater between these sites. These models are therefore of limited use in artesian situations and a separate method of predicting artesian spring interference due to groundwater abstraction is required.

The effects of water abstraction near any artesian spring in Canterbury are presently estimated by superimposing the effects of well drawdown across the site at which the spring emerges (Pattle Delamore Partners and Environment Canterbury, 2000), assuming a direct, linear, relationship between groundwater level and spring discharge. The allowed variations in pressure head due to groundwater abstraction are then limited to 10% of four times the standard deviation of natural annual pressure fluctuation. This method has not been empirically tested or extensively documented, nor does it take into account the dynamics of the spring system, the consequences of flow through a discrete point, or the cumulative effects of multiple groundwater takes.

In order to quantify spring depletion the following question must be answered:

- How does aquifer pressure relate to artesian spring discharge? Higher groundwater pressures will almost certainly increase the volume of water discharge by a spring vent, but how are these related?

To address the above question, water movement in a spring system must first be understood, including the following basic concepts:

- How does water reach an artesian spring vent? What is the primary source of water to a spring vent and what transport mechanisms are involved with the movement of groundwater to the surface?

It is hypothesised that water flow to a spring will be similar to flow to a flowing or pumping well, in that a certain piezometric pattern will form around a spring that is proportional to the spring discharge. This concept was considered in the guidelines for the assessment of groundwater abstraction proposed by Pattle Delamore Partners and Environment Canterbury (2000), but has never been observed.

The hypothesis proposed in this study is that the relationship between groundwater pressure and artesian spring flow will not be linear, or first-order. Pressure loss due to a fluid's movement is almost always a function of the fluid velocity squared. This has been observed in pipe flow (e.g. the Darcy-Weisbach equation), flow through packed beds and high flow production wells (e.g. the Forcheimer equation). The exception is Henry Darcy's experimental results with water flowing through sand filters, and his measurements on artesian wells in France (Brown, 2000). Darcy found the relationship between pressure head and flow to be entirely first-order, only dependent upon the physical properties of the sands.

1.4 Test Site Selection - Desktop Study

Site selection for data acquisition was important, as empirical testing was a major part of this research. The data provided from the test sites were to be used to observe actual pump interferences and to verify the applicability of any theoretical solution.

A desktop review of Environment Canterbury's Springs Database for the coastal central Canterbury Plains area was undertaken to determine possible test sites. Use of Geographical Information Systems (GIS) gave a good indication of the usefulness of a spring site in terms of access, existing wells that could be used as observation wells, and any consented activities (such as groundwater abstraction) in the immediate area.

The ideal site(s) would have the following properties:

- Readily identifiable artesian vents, with flow rates sufficient to induce measurable distortion of the piezometric surface.
- An existing well set-up that could serve as an observation network.
- Spring vents at the head of a small stream so that no influence from upstream (surface) activities would exist, and conditions that would allow simple installation of flow measuring equipment.

- Lack of abstracting wells in the area that could cause groundwater interference.
- Access for drilling production and monitoring wells (if required).

After identifying possible site locations of mapped springs, numerous field visits were undertaken. The occurrence of suitable artesian spring areas in Christchurch is limited and few appropriate artesian vents were identified. The final site selection consisted of one site at Halswell with large spring vents, and a second site at Brookside with a defined area of artesian inflow to a small stream.

Funding from Environment Canterbury was allocated for the installation of temporary wells if necessary, and although at first only water level observation well (piezometer) installation was planned, this also allowed for the drilling of temporary production wells.

1.5 Project Methodology

1.5.1 Determining Flow to an Artesian Spring

The pattern of groundwater flow to a spring was determined using a high density piezometer network. This involved the installation of piezometers into the shallow aquifer immediately below, and at varying distances from, the spring(s). Piezometric levels measured from the piezometers provided information about the near-spring aquifer and confirmed it as the primary source of water for the spring.

1.5.2 Artesian Pressure – Spring Discharge Relationship

To explore the relationship between aquifer pressure and spring discharge, and to observe responses to near-spring water abstraction, pumping was carried out at each test site to remove water from the shallow aquifer and thus reduce artesian pressure.

Inducing a reduction in the pressures driving an artesian spring vent, or vents, will result in reduced yield from the spring area. By varying and noting the rate of abstraction, and noting the change in spring flow, an empirical relationship between abstraction rate and spring discharge could be determined. If the aquifer parameters are known and abstraction rates are monitored, then pressure changes across the system can be estimated using existing groundwater flow models, and a relationship for change in aquifer pressure and spring discharge determined.

A second system of altering the pressure differential across an artesian vent is to simply increase the outlet, or back, pressure. Raising the level of the water outlet will increase the back-pressure and the result will be a reduction in the discharge rate of the aquifer.

In addition to gathering interference data from the abstracting wells, drawdown measurements in observation wells allowed for simultaneous aquifer testing and aquifer parameters were able to be determined for each site.

1.6 Hydrogeology of the Greater Christchurch Area

1.6.1 Geological Setting

The geology of the Canterbury Plains has been documented by a number of authors including Suggate (1963), Wilson (1976), and Brown and Weeber (1988). The following is a synopsis of the hydrogeology of the greater Christchurch area, with emphasis on the factors pertaining to artesian spring occurrence and behaviour.

The Canterbury Plains are built up of coalescing gravel fans sourced in the Southern Alps and carried by rivers toward the east coast. The inland plains are comprised predominantly of gravel, often layered and intermixed with sand and silts. The aquifer system extends hundreds of metres down with the depth of gravel reaching a verified maximum of around 630 m (Ealing-1 exploration well) on the plains and some 310 m (Resolution-1 exploration well) above the continental shelf offshore.

During Quaternary glaciations the amount of material eroded from the Alps was such that the rivers could not transport it all away, and as a result river slope increased with the upstream build-up of detritus. As the glaciers retreated the rivers became better able to remove these built up gravels, and to redeposit them on the lower plains. A consequence of this reworking was the abrasive break down of mudstones, removal of fines, increase in sorting, and a general increase in permeability of the gravels with increasing distance from the Alps. In the warmer times of interglacial conditions and associated sea level rise, fine marine sediments were deposited repeatedly onto the costal margins of the plains. This resulted in the layering of glacial outwash gravel aquifers separated by finer aquitards of marine sediments in the east and non-marine to the west (Figure 1-3). The upper postglacial surface of the coastal margin consists of reworked overbank silts and peat swamp deposits, as well as interbedded sands and gravels (Mosley, 1992).

The confining formations represented in Figure 1-3 are, in reality, far more complex in regards to composition and can include intermixing of permeable gravels as well as finer sediments. This allows for localised thinning of the confining layers, and provides a mechanism for normally deeper occurring artesian water to approach the surface.

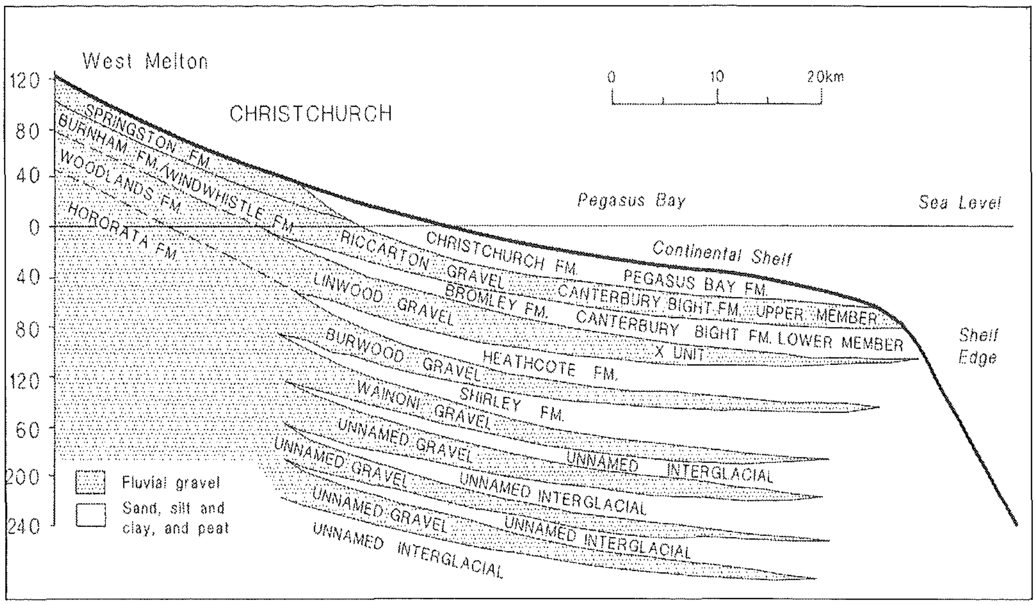


Figure 1-3 Simplified aquifer geology below Christchurch (Brown and Weeber, 1988)

Logs from the drilling investigations carried out in this project indicate that much of the shallow aquifers around artesian vents may be free running fine gravels containing some sands but with little flow-inhibiting silts and clays (Appendix D). One explanation for the lack of fines is the 'development' of the aquifer around the spring vents due to the constant water flow through the aquifer and spring system to the surface.

1.6.2 Stratigraphy

As the source of groundwater for Canterbury's artesian spring systems is most likely the shallow aquifers, only the geological formations relating to the definition of the upper aquifers will be covered. These upper formations are made up of Late Quaternary sediments of the coastal plains, and have been grouped into stratigraphic units based on the drilling log information obtained from several hundred water wells drilled in the Canterbury Plains (Figure 1-4).

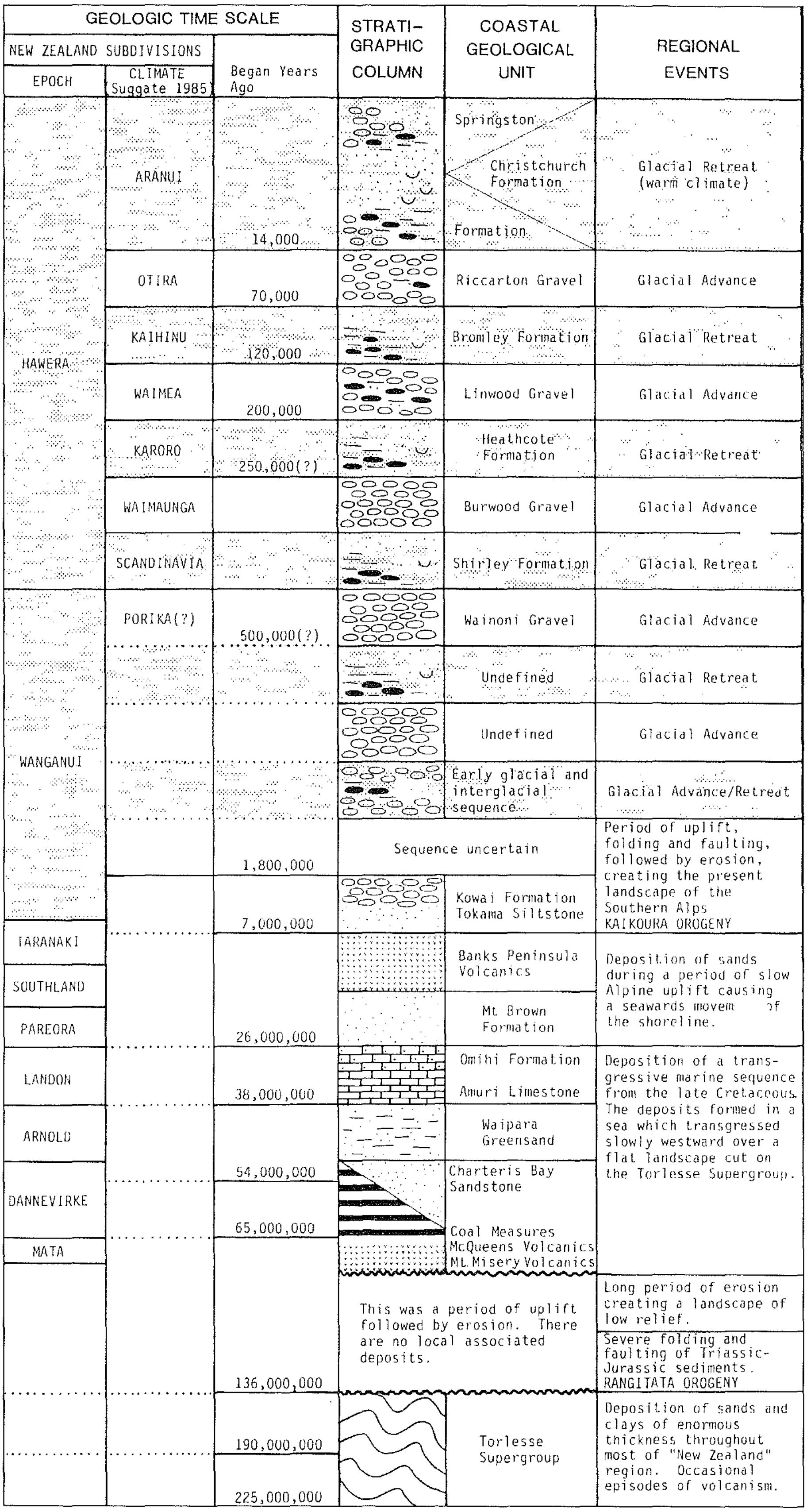


Figure 1-4 Aquifer/aquitard stratigraphy for the Christchurch area (Talbot et al, 1986)

1.6.2.1 Riccarton Gravels (Suggate, 1958; Brown and Wilson, 1988)

Forming the uppermost confined aquifer below Christchurch, the Riccarton Gravels were deposited during the last glacial periods, occurring 70 000 – 14 000 years ago. They lie on the Bromley Formation and were deposited by glacial outwash rivers as they built vast fans eastwards toward the, then, regressing shoreline. The formation occurs at a depth of 10 to 40 m, with localised shallowing to around 5 m, and ranges in thickness from a few metres to around 20 m.

The Riccarton Gravels are not easily distinguishable from the overlying Springston Formation gravels, where they are unconfined further inland. They are clearly defined under Christchurch, but grade into sands and silts with minor gravels, down-gradient, toward the coast. The offshore equivalent is the upper member of the Canterbury Bight formation (Herzer, 1981). It is described as a gravel with medium and fine sand. It is likely that the Riccarton Gravels continues its gradation to sand down gradient.

1.6.2.2 Christchurch Formation (Suggate, 1958)

Post glacial (9000-6500 years old), the Christchurch Formation is comprised of beach, lagoon and swamp sediments, and is associated with a rise in sea level at the end of the last major glacial period. The Christchurch Formation occurs along the coast between the Rakaia and Waipara Rivers. These sediments were laid down over the Riccarton Gravels and provide the upper confining layer, restricting water flow upwards and allowing artesian pressure to build in the Riccarton Gravel formation. The Christchurch Formation extends inland up the plains toward the west wedging out around Papanui/Avonhead.

The Christchurch Formation links offshore to the Pegasus Bay Formation. The occurrence of this formation prevents, or reduces, the offshore drainage of the Riccarton Gravel aquifer to the sea. The Pegasus Bay Formation represents the net accumulation of new sediment supplied to continental shelf since the return to a relatively stable sea level around 6000 years before present (Herzer, 1981).

1.6.2.3 Springston Formation (Suggate, 1958; Brown and Wilson, 1988)

The postglacial Springston Formation comprises fluvial gravels and overbank sediments, and represents the terrestrial deposits laid down at similar times to the marine Christchurch Formation. The gravel deposits are generally finer and more permeable than the older glacial outwash gravels (Riccarton Gravels). On the coastal plains the Springston Formation becomes interbedded with the finer Christchurch Formation.

The Springston formation can be subdivided into five members namely: Bleak House, Riverview, Courtney, Halkett and Yaldhurst. Of these members the most relevant to Christchurch's artesian springs is the Yaldhurst, which comprises three lithological units - overbank silts, peat deposits, and the gravel in-filled Waimakariri River channels - deposited during the last 3000 years.

The interbedding of Springston gravels in the less permeable Christchurch Formation provides a mechanism for water of the deeper artesian aquifers to approach the surface. Discrete lenses and channels of permeable gravels provide a less resistive pathway for the pressurised groundwater to move through the overlying aquitards.

1.6.3 Identification of Aquifers and Aquitards

The geological evidence provided by drilling log information has been, and is being, developed by Environment Canterbury and other water authorities to identify the principal aquifers in the inland plains and coastal Christchurch area.

The basis on which the aquifers are identified is that they are water-bearing layers that yield water in such quantities that they can be considered a practical source of water (Talbot *et al,* 1986). Five gravel aquifers have been identified in the top 250 m of sediment below the greater Christchurch area.

The upper Christchurch aquifers are made up of the Riccarton Gravel Formation, which represents *Aquifer One*, and the Linwood Gravel, which represents *Aquifer Two*. The Bromley and Christchurch/Springston Formations represent the upper aquitards. Although these formations, and those deeper, are extensive and capable of confining groundwater under considerable pressure, there is flow through the layers (and so hydraulic connectivity) in places where coarser sediments occur. The areal extent of the uppermost confining layer (Christchurch and Springston Formations) is represented in Figure 1-5. This layer provides the mechanism for the Riccarton Gravels to develop artesian pressures, and hence represents the extent of possible artesian spring occurrence.

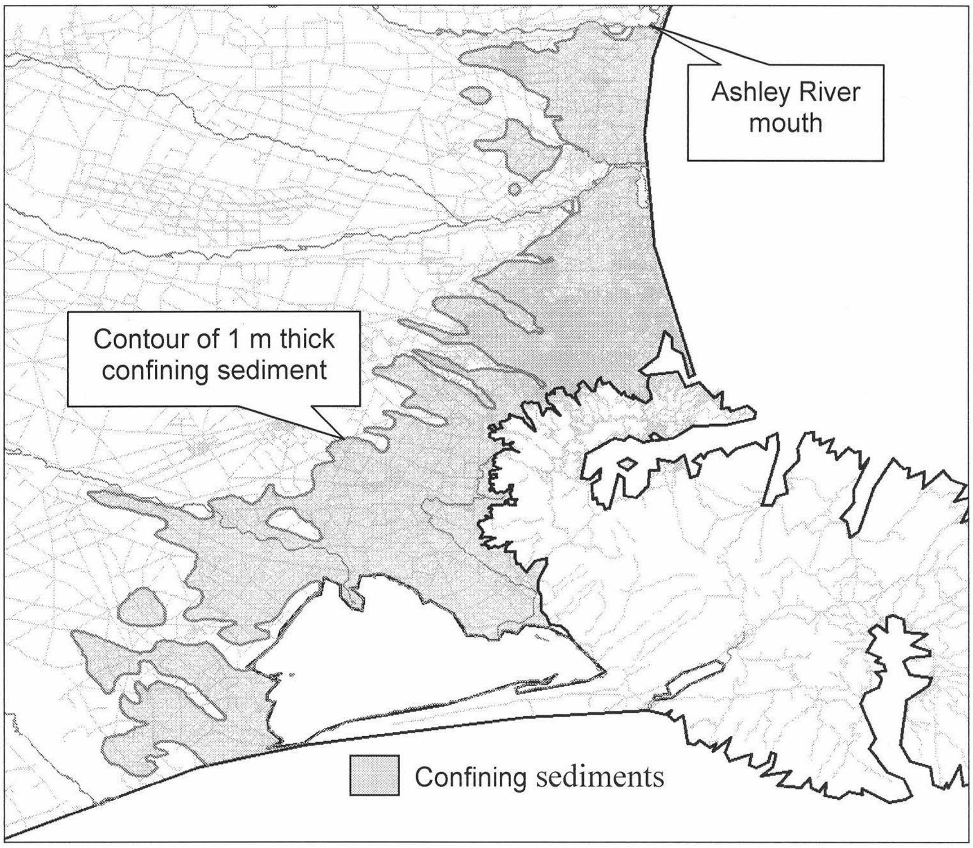


Figure 1-5 Extent of 1 m+ thick confining sediment of upper aquitard (Chch Fm)

1.6.4 Recharge of the Shallow Aquifers

The groundwater investigation and interpretation of well data, by the North Canterbury Catchment Board (Talbot *et al*, 1986), has resulted in a simplified model of the Christchurch aquifer system. Further interpretation of hydrogeological and hydrological information has identified a number of possible sources of groundwater recharge, and a physical model of the Christchurch groundwater system is represented schematically in Figures 1.8 and 1.9.

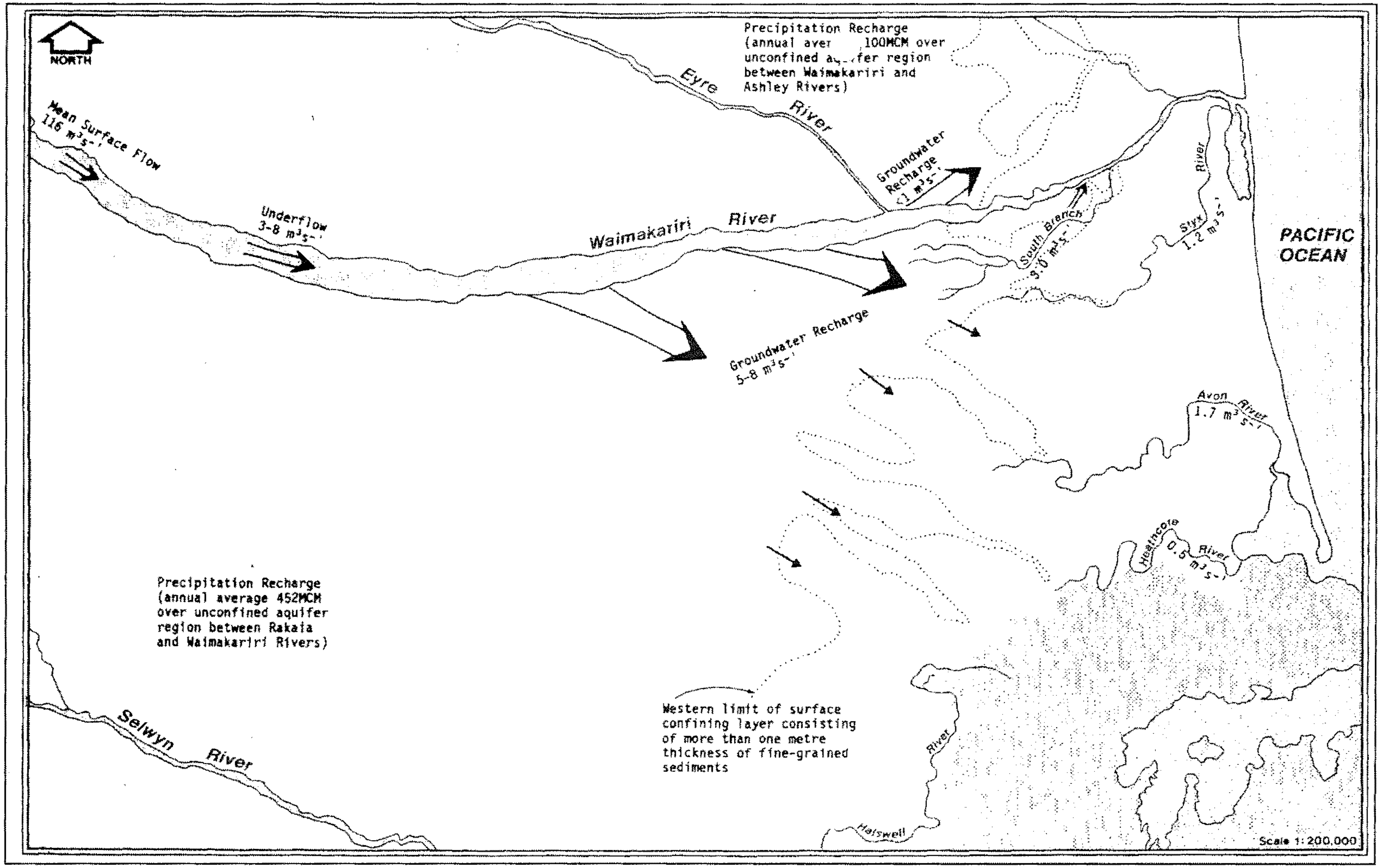


Figure 1-6 Hydrological components of the Christchurch groundwater system (Talbot et al, 1986)

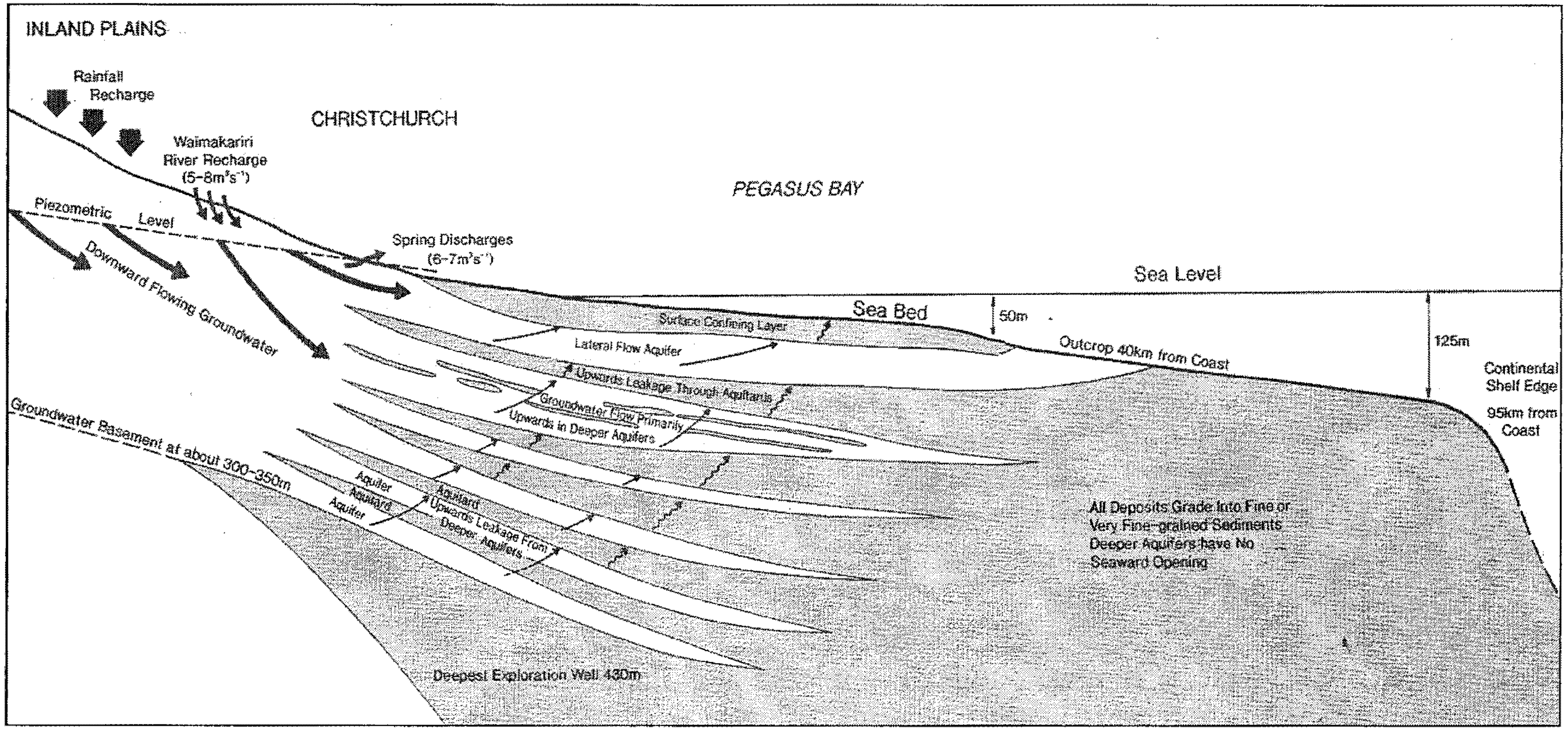


Figure 1-7 Canterbury Plains aquifer model (Talbot et al, 1986)

The following have been identified as probable sources of groundwater recharge from the models proposed by Talbot *et al* (1986):

- Recharge from upper central plains aquifers. The lack of an extensive, continuous confining layer over the upper plains allows rainwater, and river water, to percolate down into the aquifers of the upper plains. The hydraulic gradient of the aquifers reduces to the east and groundwater moves seaward. As a result of the eastward movement the upper plains groundwater enters the confined aquifers and provide the main source of groundwater recharge for the Christchurch aquifer system.
- Recharge from Waimakariri River seepage that enters the groundwater system around McLean's Island. The majority of the water lost from the Waimakariri in this region is considered to recharge the shallow artesian aquifer supplying Christchurch's spring-fed rivers, however some water may percolate to the deeper aquifers.
- Recharge from deep groundwater leakage. The hydraulic pressure in the gravel aquifers under Christchurch increases significantly with depth, and the resulting pressure differential between successive aquifers will allow upwards leakage of deeper groundwater through the adjacent aquitards. This upward leakage provides a recharge rate that will be proportional to the pressure differentials across the aquitard but is insufficient to significantly increase the upper aquifer pressure.

1.7 Thesis Format

This thesis is arranged into six chapters, as follows:

Chapter 2 discusses the nature of artesian springs, where these spring's systems can occur, how they are likely to operates, and where they have been found to occur in the greater Christchurch area. This chapter also addresses the hypotheses of the source of artesian spring water in the study areas.

Chapter 3 provides an introduction to theoretical equations of flow through porous media, and provides a theoretical background for the hypothesis of an aquifer pressure – spring discharge relationship.

Chapter 4 outlines the collection of field data, testing and hydrogeological backgrounds of the test sites used.

Chapter 5 presents findings of the field data, comparing the empirical relationships between aquifer pressure and spring discharge with the hypothetical solutions, and discusses its implications in terms of groundwater management and spring depletion.

Chapter 6, summary and conclusions, provides a synopsis of the previous chapters with some suggested topics for future work in the area of artesian spring interference.

2 Artesian Springs

2.1 Introduction

This chapter outlines artesian spring occurrence and hypothetical mechanics, and gives an overview of the artesian spring systems in the greater Christchurch area. Starting with spring terminology, this chapter then looks at spring models, the distribution and occurrence of these systems, the impacts that groundwater abstraction could have and how these impacts can be investigated in the field.

2.2 Artesian Spring Terminology

Bryan (1919) identifies a spring as "a place where water issues from the ground and flows, or where it lies in pools that are continually replenished from below". The Glossary of Hydrology (Lo, 1992) defines a spring as "a place where groundwater flows naturally from a rock or soil onto the land surface or into a body of surface water".

A seep, groundwater appearing continually at the surface in small quantities, is often distinguished from spring flow; an example is Bouwer (1978) who defines a seep as water oozing out of soil or rock without distinct trickles or rivulets. Bell (1990), however, states that springs and seepages should both be regarded as sites of groundwater discharge, and this is very true for Canterbury's artesian springs, as a seep will likely develop into a spring over time.

The term 'artesian' has a range of definitions. Various texts intermix the terms 'artesian' and 'confined' to refer to an aquifer in which water will rise to a height higher than that at which the aquifer is first encountered. This is not, however, the original definition of artesian and as a consequence mixed interpretations of the term 'artesian' occur in both groundwater science and everyday English.

The word 'artesian' derives from the town of Artois, France, where the Carthusian monks dug the first artesian well in 1126, thus the term is more geographical than technical. The well was only a few inches in diameter, but it penetrated strata impermeable to water, reaching a lower layer containing water under pressure. The water rose in the borehole and *flowed spontaneously* out of it (Gies and Gies, 1994). Wells that could flow without the use of pumps would be readily distinguished from other wells, and thus were classed differently to wells that did not free flow.

The term 'confined' is given to an aquifer in which pore pressures are in excess of that due to fluid mass ($\rho \cdot g \cdot h$), that is, the water-atmospheric pressure boundary, or piezometric surface, is above the level of the aquifer. A confined aquifer is only artesian if the water pressure of the aquifer is sufficient to exceed ground level, and potential for water to flow freely. If the artesian pressure recedes below ground level, and water will no longer flows freely, the aquifer becomes sub-artesian. Thus all artesian aquifers are confined, but a confined aquifer is not necessarily artesian (Figure 2-1).

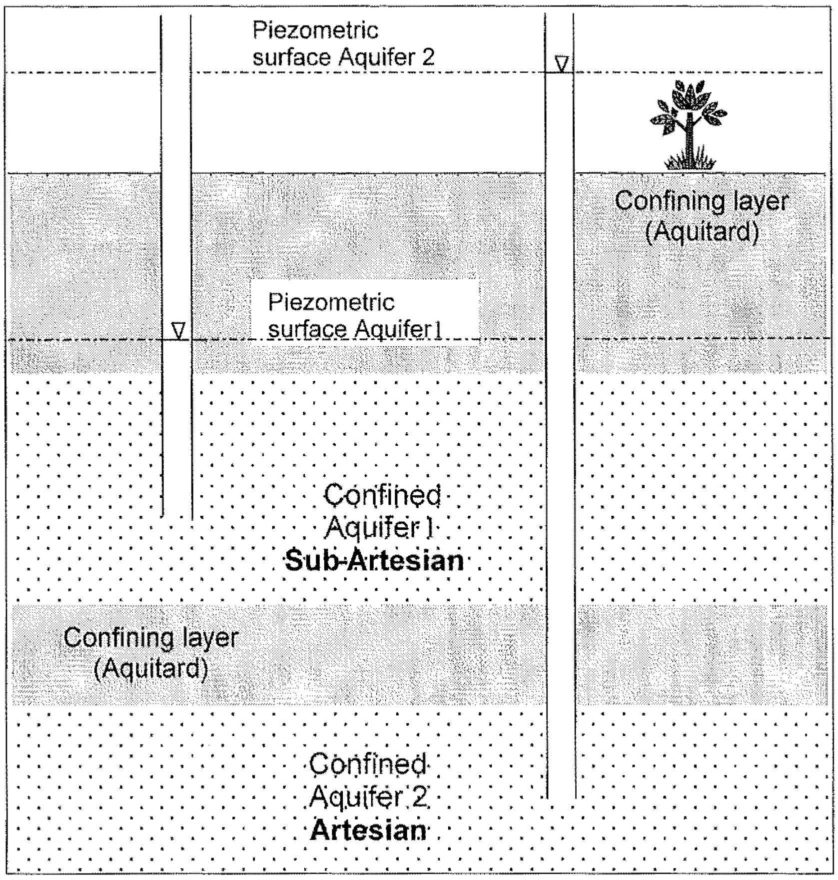


Figure 2-1 Confined, artesian (lower) and sub-artesian (upper) aquifers

This thesis adopts Scheieferdecker's (1959) definition of an artesian spring as being "water that issues (to the surface) under pressure though some fissure or other opening in a confining formation that overlies an aquifer". In certain texts, artesian springs are also referred to as fissure, or ascending springs, terms derived from their occurrence and physical character.

Artesian spring nomenclature adopted for this thesis is as follows (see Figure 2-2):

- *Source aquifer* is the primary source of water discharging from the spring. This aquifer provides the driving pressure forcing groundwater through the spring system, and the primary storage of groundwater that will be discharged.

- *Artesian vent* is the point at which water exits the groundwater system and becomes surface water, ranging from millimetres to metres in diameter.

- *Spring/vent fissure* is the pipe-like structure in an aquitard linking the source aquifer and the artesian vent. Spring fissures can occur as single, generally larger, discrete points of discharge or as part of a 'swarm' of fissures over a wider area of artesian water inflow.

- *Pre-development head* is the pressure head present in the source aquifer with no interference from spring discharge (i.e. no springs present or flowing).

- *Spring pool head* is the elevation height of the pool into which a spring vent discharges.

- *Piping* is groundwater flowing through localised zones, or pipes, of relatively highly hydraulically conductive material. In the case of artesian springs, piping is the process of groundwater flow through a vent fissure in an aquitard.

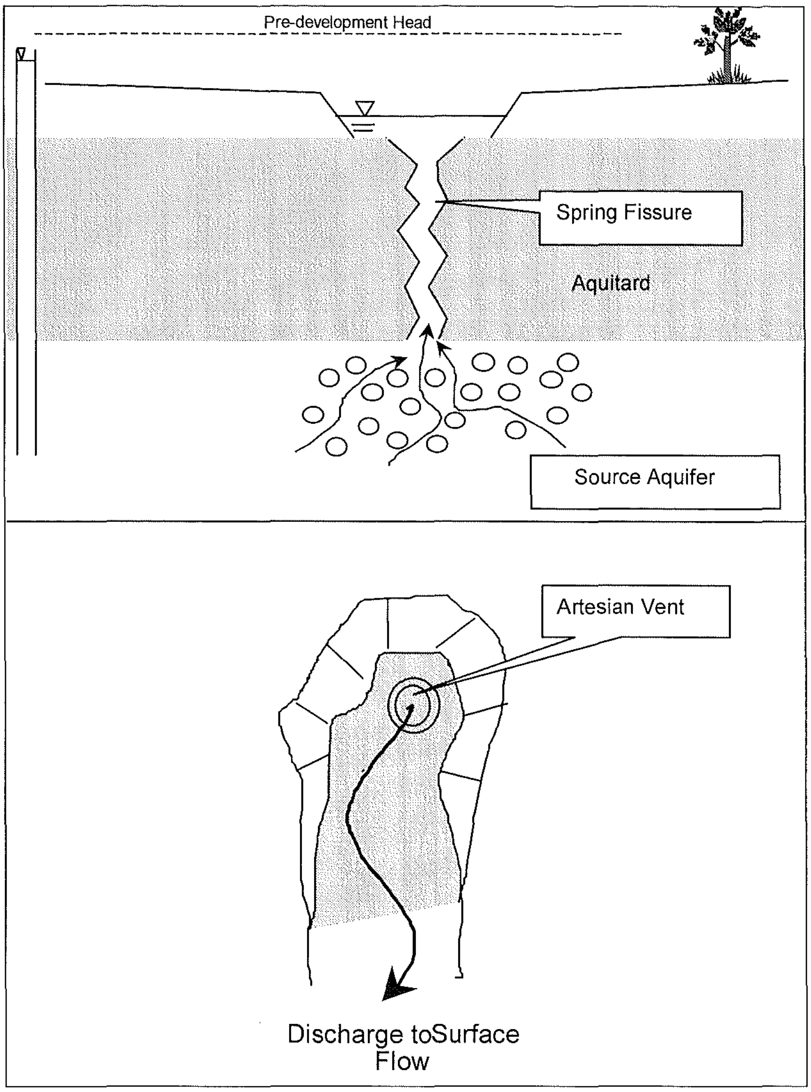


Figure 2-2 Stylised artesian spring system

2.3 Artesian Spring Systems

2.3.1 The Artesian Spring Model

The hydrogeological parameters for an artesian spring include: a piezometric surface above ground level the existence of a confining layer and a source of water sufficient to supply the spring.

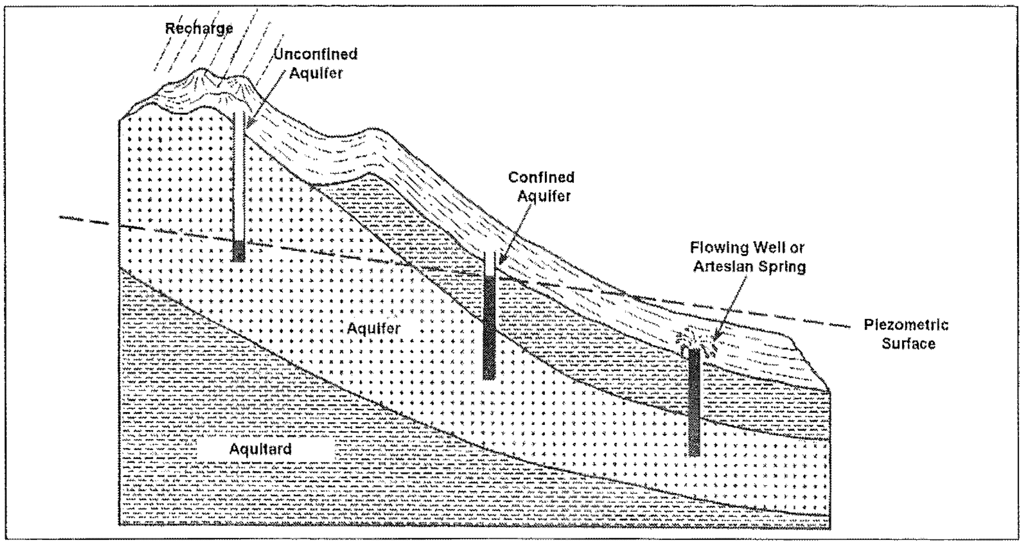


Figure 2-3 A confined aquifer system (modified after Fetter, 1994)

Figure 2-3 shows a simple artesian spring system in which the following physical characteristics contribute to spring formation and flow:

- *A sloping aquifer*: The physical gradient of the aquifer provides the mechanism for groundwater to transition, in this case, from unconfined to confined conditions. In the case where the aquifer does not slope, then a thickening of the upper confining layer in the direction of flow is required to induce an increase in aquifer water pressure.
- *Recharge area above outflow.* The higher the elevation of the recharge area compared to the spring outlet the greater the potential for flow. The recharge elevation controls the maximum pressures that can be generated in the confined aquifer downstream.
- *Aquifer bounded, above and below, by low permeability material.* Containment of groundwater within laterally extensive aquicludes (or aquitards) allows pressure to build without (or with little) loss of water, or dissipation of fluid pressure to other permeable formations.
- *An aquifer system with average recharge in excess or equal to discharge*: To generate and maintain pressure in the source aquifer the rate of water into the system must be, on average, greater or equal to the rate of water lost from the aquifer or pressure will drop and springs will cease to flow. Water mining by irrigation abstraction, for

example, will therefore have adverse effects on artesian spring systems.

Artesian springs commonly form in karst aquifers, where water is stored in joints and fractures, rather than the pore spaces between rock grains, and dissolution of the calcareous material results in the formation of large pipes and caves. The very high hydraulic conductivities of these structures, and ability for the limestone to produce very high gradient aquifers, means karst aquifers can potentially yield high volume springs. An example of a karst-based artesian spring is Waikoropupu in Northwest Nelson. The rate of resurgence of these springs is 1.2 million cubic metres of water per day, or around 14 000 l/s (Edgar, 1998). In contrast, gravel aquifers have, in general, much lower hydraulic conductivities and lower angles of recline, restricting both the rate of movement and the range of pressures of water in them. As a consequence, discharge from gravel-based artesian springs tend to be far smaller in magnitude than those of karst-based springs and in Christchurch gravel-based springs commonly discharge less than 40 l/s.

2.3.2 Flow to Artesian Springs

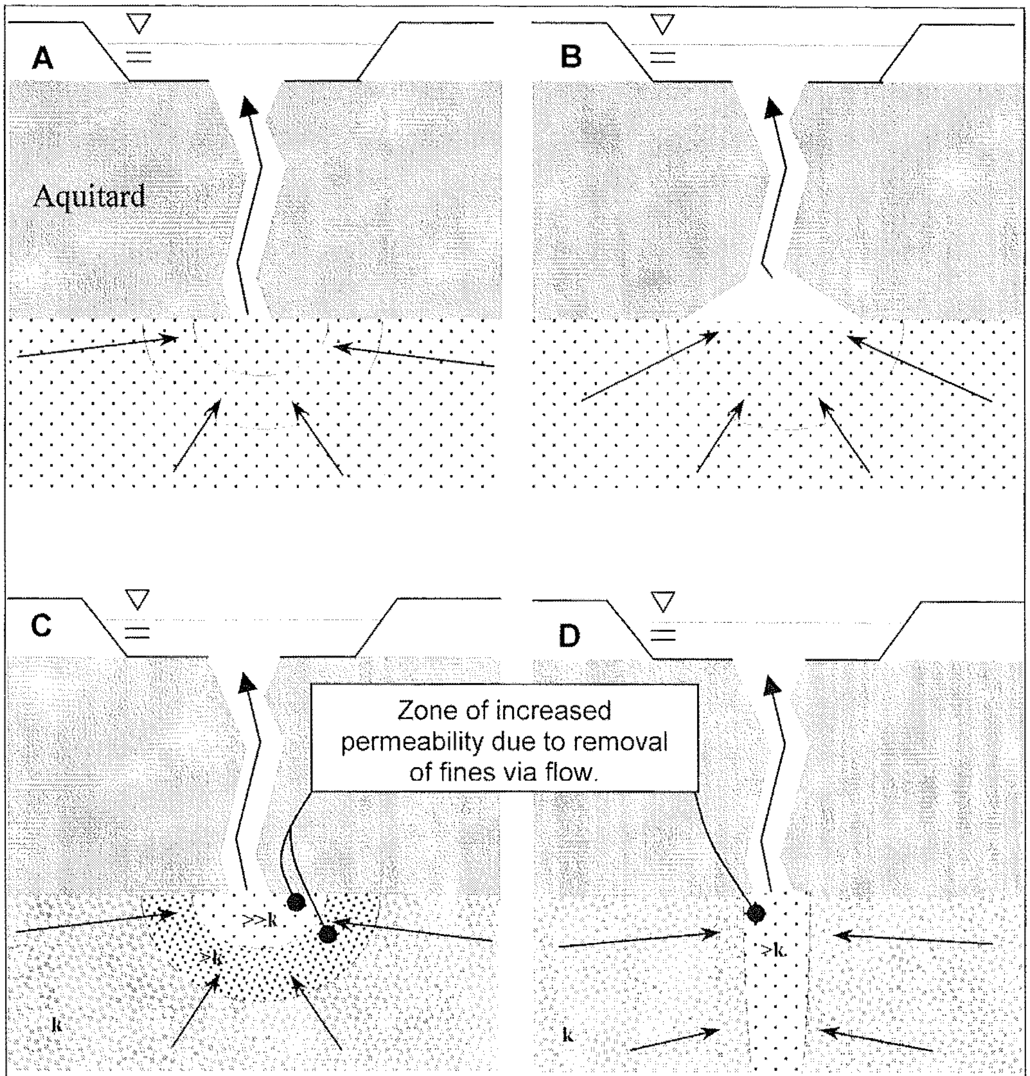
In a gravel aquifer, three flow stages occur in order for groundwater to discharge from an artesian spring. Each of these flow stages have differing characteristics and each play a part in controlling the final discharge from the spring as follows:

1. Water in the source aquifer begins stationary, or near stationary. The presence of a nearby outlet then causes the groundwater to travel at a low flow rate toward the spring fissure. The velocity of the flowing water begins to increase proportionally to the cross-sectional area through which it is travelling as it nears the spring fissure.

2. Immediately before entering the spring fissure, the cross-sectional area through which the water is flowing is at a minimum due to the groundwater flowing to a constricted point of outlet, and compounded by the presence of the aquifer matrix, further reducing flow area. The result is a very high rate of flow through the porous medium of the aquifer until the water enters the spring fissure.

3. Upon entering the spring fissure, the lack of aquifer matrix allows the groundwater to flow less torturously, and form pipe-like flows with relatively large pore space and high hydraulic conductivity. This allows the fluid velocity to slow, but more room to swirl and become turbulent.

Figure 2-4 is a schematic representation of possible artesian spring configurations in a gravel-based aquifer. All configurations require groundwater to move from near stationary to relatively high velocities in order to achieve the flows observed from the springs. A consequence of high velocities, and hence high-energy flow, is that finer sediment can be more readily transported, resulting in localised sorting of the source aquifer, and an increase in hydraulic conductivity.



Possible flow to a surface vent: A Hemispherical flow to small fissure, B Hemispherical flow to a large entranced fissure, C Zone of increased permeability D Predominantly radial flow induced by zone of high permeability.

Figure 2-4 Possible artesian spring configurations

Configuration A: An isotropic source aquifer feeding a vent fissure of uniform cross-section. This configuration requires the groundwater to pass through a narrow entrance to the vent fissure and so will require a relatively high entrance velocity.

Configuration B: An isotropic source aquifer that feeds a large opening to the spring vent fissure. Here the maximum velocities of the groundwater in the matrix, for the same spring vent discharge, are reduced because the cross-sectional area of the fissure-aquifer interface is much greater.

Configuration C: An increase of hydraulic conductivity as a result of development of the aquifer, close to the spring vent, by the flowing groundwater. The easily transported fines are removed to give a more sorted aquifer matrix, and as a consequence a zone of higher hydraulic conductivity. A reduced maximum velocity of groundwater is therefore required to maintain the spring vent discharge.

Configuration D: An increase in depth of a zone of higher hydraulic conductivity will result in more radial flow, rather than hemispherical, to the spring fissure from the source aquifer resulting in a larger cross-sectional area of flow.

2.3.3 Drawdown Model

Discharge from a spring is identical to the situation of a free-flowing artesian well, and is similar to a pumping well. A consequence of water movement is that springs will develop their own piezometric signature in the source aquifer, including a *cone of depression*, or drawdown cone, similar to that associated with a pumping well. As with a flowing well, the vertical axis of the cone of lower pressure will coincide with the centre of the flow area where groundwater velocities are highest.

A piezometric pressure change occurs because saturated flow through porous media of uniform cross-sectional area results in a uniform reduction of fluid pressure with flow distance, proportional to the fluid velocity and the hydraulic properties of the media (Figure 2-5).

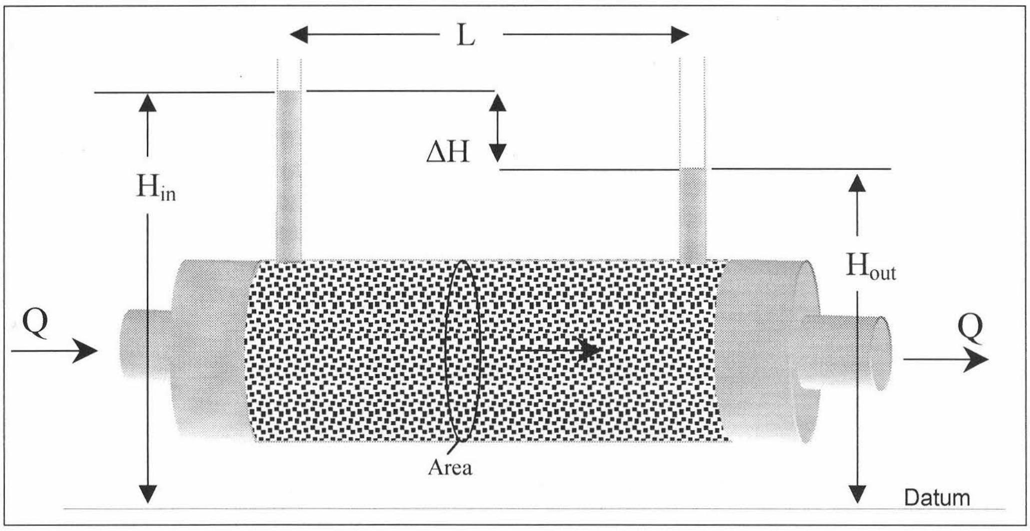


Figure 2-5 Pressure loss due to flow through a soil

Flow to a point, such as a well, will produce an identical pressure drop proportional to the velocity at which the fluid is moving, however, from the continuity equation, for an incompressible fluid flow is equal to the fluid velocity multiplied by the cross-sectional area of flow or:

$$Q = vA \qquad (2\text{-}1)$$

If the flow through the system, Q, is constant (steady state) then the fluid velocity, v, is inversely proportional to cross-sectional area, A, and hence the drop in fluid pressure toward a point will also be inversely proportional to the area of flow:

$$A \propto \frac{1}{v} \qquad (2\text{-}2)$$

A fully penetrating well, screened across the entire aquifer, will have radial flow moving towards it and the piezometric pressure drop will be proportional to the radial distance from the well, r, as the function of the flow area:

$$A = b\pi r^2 \qquad (2\text{-}3)$$

where b is the aquifer thickness.

A point of outlet from an aquifer through an aquitard will have hemispherical flow to it. The pressure drop will again be proportional to the flow area perpendicular to flow direction, however the change will be more rapid while the radial distance is less than the saturated depth, $r < b$:

$$A = 2\pi r^2 \tag{2-4}$$

From equation 2-4, the rate of cross-sectional flow area change is a function of radial distance squared, r^2, from the exit point, as opposed to radial flow where area is a function of the radial distance, r. When the radial distance from the exit point is equal to, or exceeds, the aquifer thickness, then the equation for the flow area becomes equation 2-3. A partially penetrating well will have some horizontal radial flow as well as vertical flow, and a velocity profile as an alternative function of flow area, between purely radial and purely hemispherical flow (equations 2-3 and 2-4).

An artesian spring is most likely to have water flowing to it from all directions in a hemisphere around the point at which water leaves the aquifer and enters the vent fissure through the aquitard. The piezometric pattern around an artesian spring will therefore be similar to that of a fully penetrating well pumping at a similar rate, however, while the radial distance is less than the aquifer thickness the change of pressure drop toward the spring will be greater, and accordingly the velocity of groundwater in the aquifer will be higher.

The consequence of non-horizontal groundwater flow to a point is that currently accepted groundwater models should be used with caution, as non-horizontal flow invalidates assumptions employed by many of the theoretical models. However, as previously mentioned when the observation data are collected from a distance greater than the thickness of the aquifer then the flow induced drawdown should be comparable to the current models, and they will be valid tools for estimating aquifer response to the removal of water.

The installation of high-resolution piezometers into the source aquifer of a spring will therefore show a reduction in artesian pressure toward a spring vent in all directions, and from the data obtained, namely pressure drawdown and spring discharge rates, an approximation of the hydraulic conductivity of the source aquifer can be determined.

2.3.4 Discharge Controls

The natural flow of springs is controlled by a number of hydrologic and geologic factors. These include the amount and frequency of water inflow, the hydraulic conductivity of the aquifer, the water pressures within the aquifer, and the hydraulic gradient. To a lesser degree, influences outside the aquifer such as atmospheric pressure systems and ocean tides will also influence the performance of an artesian spring system by altering aquifer pressures. Further physical characteristics of a spring, such as cross-sectional discharge area, and rate at which the discharged water can be removed (dependant on the stream gradient and profile) will also contribute to discharge control.

Formation of an artesian spring will occur when aquifer pressures reach and exceed ground level at a point where localised weaknesses in the overlying confining layer allows groundwater to move to the surface. The predominantly fine-grained nature of sediments of the upper confining layer of the greater Christchurch area is such that as groundwater moves through the confining layer and discharges onto the surface, erosion and fluid transportation of the confining layer materials will occur. The consequence of this erosion is the reduction of resistance of the confining layer to groundwater seepage, and the seep will continue to increase in size and discharge rate until the spring system reaches equilibrium. Down-stream erosion and head-scarp retreat of the confining layer may produce 'swarms' of vents over a distance of some tens of metres (Cameron, 1993), or as is often the case of thick confining layers the spring may remain as one large vent.

Swarms of springs are most likely to occur in areas where the confining layer is relatively thin. As a seep develops into a spring, downstream erosion and head scarp retreat will occur. The consequential thinning of the confining sediments, both upstream and downstream, will reduce the confining layer's resistance to flow, and allow groundwater inflow over a more widespread area. Where the confining material is thicker the effect of erosion from spring development is lessened. Any zones of weakness in the thicker confining sediments are less likely to propagate far enough through the sediments to allow further vent formation (Figure 2-6).

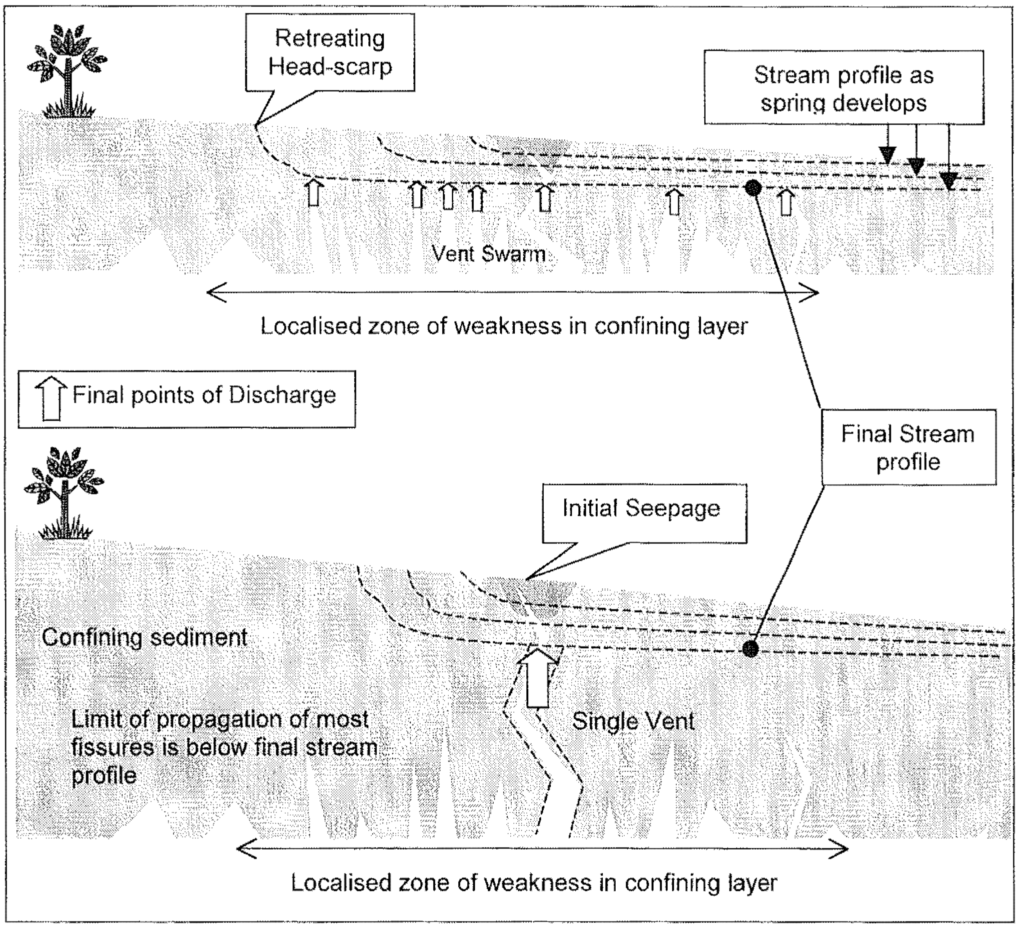


Figure 2-6 Hydrogeological scenarios controlling vent morphology

2.4 Artesian Spring Distribution

2.4.1 Canterbury Plains Model

A simplified model of the artesian springs in the central Canterbury Plains is represented in Figure 2-7.

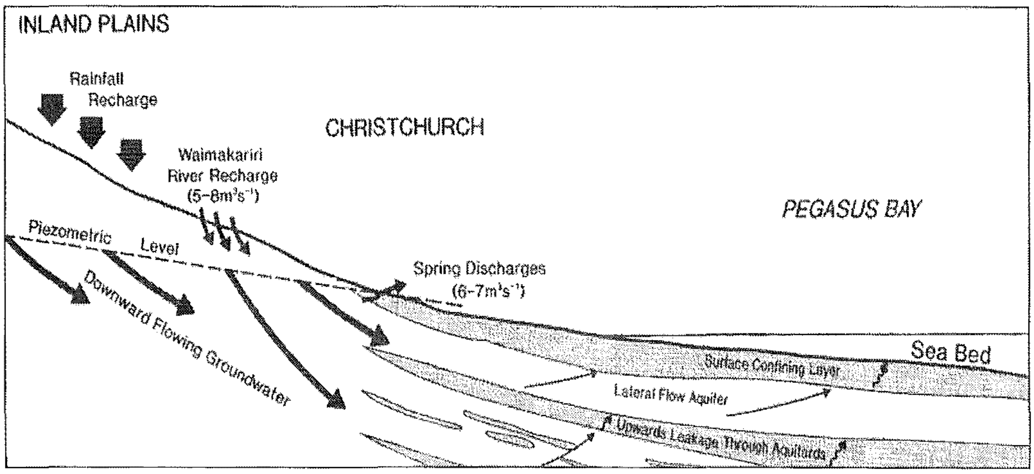


Figure 2-7 Simplified section through Canterbury Plains (modified from Talbot et a,l 1986)

The gradient of the Canterbury Plains is greater than the hydraulic gradient of the aquifers (figure 2-8). Starting below ground level inland, the piezometric surface of an aquifer can exceed ground level further eastward, down-gradient toward the Canterbury coast. The point at which the piezometric surface above sea level equals the topographic height of the plains represents the western boundary for artesian spring occurrence.

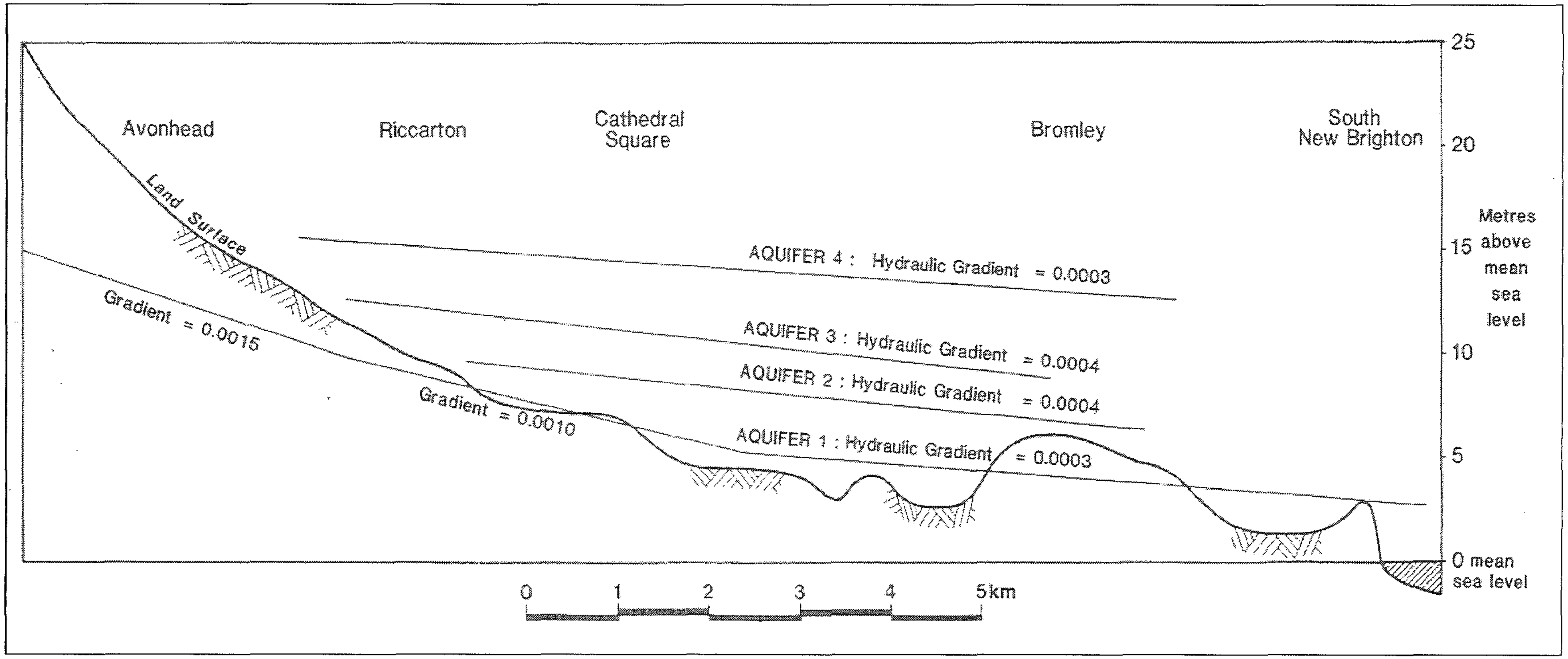


Figure 2-8 Piezometric cross-section showing aquifer gradients and pressure heads (Talbot et al, 1986)

Assuming that the uppermost (shallow) artesian aquifer is the primary source of water feeding artesian springs around Christchurch, then plotting the piezometric surface data for these aquifers from Environment Canterbury groundwater observations with topographic contours of the Canterbury Plains from Land Information New Zealand (LINZ), should identify the regions of artesian pressures. Further plotting of previously mapped upper confining layer contours from LINZ for the greater Christchurch area creates a more complete map of the physical potential for the occurrence of artesian springs by reducing the regions of artesian pressure erroneously indicated by piezometric data which were interpolated in some areas (Figure 2-9).

As a result of fluvial erosion, the artesian spring-fed streams of greater Christchurch are incised into the upper confining layer to varying depths, ranging from less than 1 m to more than 4 m. Consequently artesian vents also occur when confined pressures are below general ground level but above the incised streambed. The result is that parameters for artesian spring occurrence should be modified, by including localised incision into topography, to take into account near ground level water pressures.

2.4.2 Mapped Extent

When known artesian spring locations are extracted from Environment Canterbury's Springs Database and applied to the topographic and piezometric data, it becomes apparent that the majority (90%) of artesian springs occur where the confining layer exists with a thickness of less than 5m. These data are consistent with previous research; Cameron (1993) observed that the majority of artesian springs around the Avon River occur at depths to gravel (top of interbedded Springston Formation) of between 1 m and 10 m. The GIS model indicates that confining layers in excess of about 5 m inhibit the formation of artesian springs, thus maximum artesian pressures alone cannot be used to predict the occurrence of artesian springs. Figure 2-9 shows the intersection of piezometric surface and topography for an estimated incision of

1m (dotted line); artesian springs should only occur down-gradient of the intersection. When positions of known artesian springs are applied, there is good correlation with the intersection of piezometric and topographic contours.

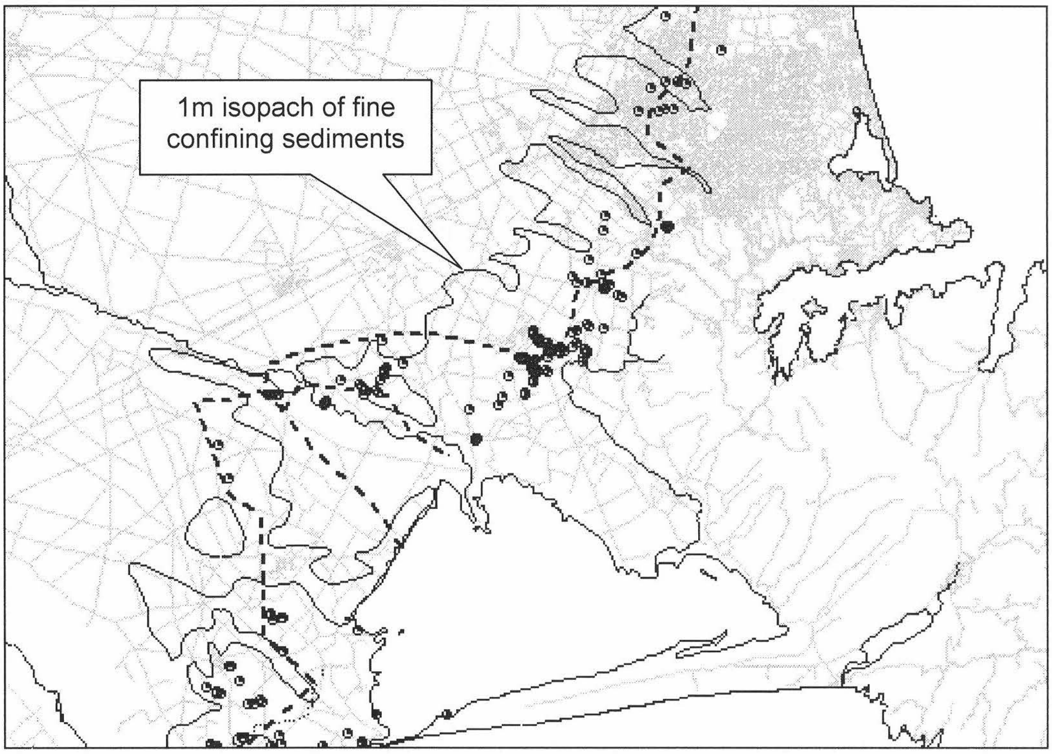


Figure 2-9 Piezometric - topographic intersection (dotted) and known artesian spring positions

2.4.3 Source Aquifers

The previous assumption that the most likely source of water for an artesian spring is the shallowest confined aquifer is based on the hypothesis that the shallowest aquifers provide the shortest route from the aquifer to the ground surface. Although piping from lower aquifers though the overlying aquifers with little interaction may be possible, via a vertical channel of clean gravels for example, a spring fissure would have to pass through the high permeability material of the aquifer which would tend to dissipate any higher flow pressures and thus inhibit direct recharge of the artesian system from deeper aquifers.

The hypothesis that only the shallow aquifer directly provides water to the artesian springs is confirmed by the lack of mounding pressures observed in the shallow aquifer. The deeper Christchurch aquifers, however, are under higher pressures, and upward leakage of deeper water through aquitards has been identified as an important recharge mechanism for the shallower aquifers.

The presence of a piezometric pattern the uppermost aquifer will prove two things:

1. That the upper aquifer is the primary source of groundwater supplying the spring. Consequently any groundwater abstraction from this aquifer will have a direct, immediate effect upon spring discharge. Upward leakage from deeper aquifers, and the implied hydraulic connection between aquifers, means that abstraction from deeper aquifers may also affect spring discharge, but to a much lesser extent. To avoid direct spring interference, abstraction should be carried out from deeper aquifers wherever possible.

2. That pressure loss due to groundwater movement occurs. If this pressure loss is not directly proportional to groundwater velocity then spring discharge could have a complex relationship to artesian pressure. This will be discussed in the following chapter.

2.5 Consequences of Groundwater Abstraction

2.5.1 Abstraction from the Confined Aquifers

All abstraction from the uppermost confined aquifers will affect water levels within the aquifer, and in turn affect spring discharge. An example of this is seen in monitoring of spring-fed streams in western Christchurch (Cameron, 1993), where very good correlations between groundwater levels and stream base flow were observed. Cameron also indicated changes in the spring-fed

Avon River's base flow due to groundwater abstraction, and it is therefore likely that groundwater abstraction will affect spring discharge.

Pumping creates a localised vortex of low pressure around a well, commonly termed a 'cone of depression', as well as contributing to overall aquifer groundwater level reduction. If a pumping well is located near a spring in the same aquifer, it will interfere directly with the artesian spring discharge by inducing its associated zone of low pressure across the spring system.

Removal of water from a confined aquifer can cause a more rapid reduction of hydraulic pressure in the aquifer than removal from a comparable unconfined aquifer, due to the storativity of confined aquifers being much lower than that of unconfined. Therefore the effects of comparable abstraction on a confined aquifer will be more severe than that from an unconfined, with rapid changes in aquifer pressure as water is removed. Reduction in pressures in the deeper aquifers will also reduce the upward leakage recharge to the upper aquifers feeding artesian spring systems.

2.5.2 Abstraction from the Inland Plains

Figure 2-8 shows that the unconfined aquifer of the central Canterbury Plains has a greater hydraulic gradient than that of the Christchurch's confined aquifers. Assuming the hydraulic conductivities of the aquifers undergo a gradational change then the cause of the most abrupt gradient reduction will be aquifer pressurisation due to confinement. This means the confined aquifer gradient will be controlled more by drainage from the aquifer than the rate at which water is entering.

An up-plain reduction in water level will reduce the efficiency at which the water draining from artesian springs in the lower plains is replaced. The effects on the confined aquifers, however, will be relatively small until water levels in the recharge area reduce to less than the confined aquifer gradient.

This is supported by wells in the lower plains often having a standard deviation in water levels of less than 1 m, compared to wells in the unconfined aquifer zone which can have standard deviations in excess of 15 m (Appendix A).

2.6 Springs as Indicators of Aquifer Stress

Springs are a natural window into an aquifer; their presence reveals groundwater potential and may help locate a useful source of water. Springs are indicators of the general state of the hydrologic system. When groundwater levels decline, either from pumping or a lack of precipitation, the change is nearly always reflected in lessened spring flow. Many artesian springs have reportedly stopped flowing as a result of lowered groundwater levels.

Advantages of using springs as indicators:

- The temperature and chemical content will provide a good indication of aquifer water quality, and indicate stress on the aquifer system as aquifer mining may alter the influence of recharge regimes. For example, a chemical change that indicates more river recharge may be indicative of poor aquifer performance either upstream and/or from the aquifers deeper down, as a result of a reduction in upward leakage.
- In areas where no formal water level data record is available, then anecdotal spring performance, and evidence of previous spring occurrence, could be used to indicate trends in regional water levels and hence aquifer health.

Disadvantages of using springs as indicators:

- It is much easier to obtain groundwater level data from monitoring wells than it is to measure discharge from a spring. Springs also often provide constant nutrients and relatively stable water temperatures that encourage flora, which can quickly affect the efficiency of water flowing from the springs and the accuracy of many measuring systems, such as flumes and weirs.

- Small changes in confined aquifer pressure often mean large changes upstream where the aquifer is less, or un-, confined. Small changes in the aquifer pressure are harder to detect via flow measurement, compared to piezometric level data from monitoring wells.

In terms of groundwater quantity and availability, it is unlikely that artesian springs will provide a more useful tool to indicate aquifer health than correlation of piezometers in the same aquifer.

Springs are, however, a natural source of information about groundwater quality. As a constantly flushing source of groundwater, a spring system will show changes in water chemistry far more rapidly than a static piezometer would, and will be very useful in monitoring aquifer water quality.

It should be noted that this thesis is concerned with water quantity and does not include analysis of the water chemistry or quality of Canterbury's artesian springs, or their respective aquifers.

2.7 Chapter Synthesis

An artesian spring is: a source of water issuing to the ground surface through a fissure or opening in a confining layer as a result of artesian pressure within the source aquifer.

The source of water is most likely to be the uppermost confined aquifers. Springston Formation gravels, interbedded with Christchurch Formation, allow localised thinning of the confining sediments and high artesian pressures will exploit any weakness in the confining layer, initially forming a seep allowing water to drain from the source aquifer. The continual movement of water from the source aquifer to the surface will serve to increase the hydraulic conductivity of the aquifer immediately below the spring vent, and through the confining layer, by the removal of fine sediment.

Artesian spring discharge is controlled by: the pressure difference across the spring, between the hydrostatic pressure of the aquifer and the final pressure at which water is discharged from the spring vent; the cross-sectional area of the spring vent; and the hydrogeological parameters of the aquifer and spring fissure.

Groundwater flow to artesian springs in the Christchurch gravel aquifers will be similar to groundwater flow to wells. The piezometric pattern formed by a flowing spring will be controlled by discharge rate and the hydraulic conductivity, and storativity of the source aquifer. The presence of a piezometric pattern around a spring system in the upper aquifer will confirm that the uppermost aquifers are the primary source of groundwater supplying the spring systems occurring in Canterbury's gravel artesian aquifer systems.

3 Groundwater Flow

3.1 Introduction

This chapter reviews groundwater theories and principles pertaining to the phases of groundwater flow in an artesian spring system. In particular, it addresses the consequences of high velocity flow, what flow regimes are likely to be present in the spring systems of the study areas, and the implications of turbulent flow and associated turbulent energy losses. The objective of this chapter is to provide a theoretical background and reasoning for the hypothesis that the relationship between artesian pressure and spring flow is non-linear.

Of the various types of spring, groundwater flow in an artesian spring system is, theoretically speaking, one of the least complex cases of spring flow to explore, as:

- The source aquifer is entirely saturated so the area through which groundwater is flowing remains constant and does not change with drawdown;
- The source aquifer is often very large compared to the size of spring, and will be treated as having infinite volume and extent;
- As opposed to pumped wells or recently uncapped artesian wells whose piezometric patterns vary with time, flow from artesian springs will be treated as steady state, with the piezometric surface being at equilibrium.

The implications of high velocity groundwater flow in a gravel aquifer are not extensively documented. This is largely due to the fact that in most cases groundwater moves very slowly through an aquifer and, generally, field experiments can be designed to avoid areas of high velocity such as aquifer flow close to a pumping well. Some of the effects of high velocity groundwater flow, however, are observed in groundwater wells, and well loss and well efficiency has been investigated extensively since Jacob (1947). Although generally associated with head loss through a well screen, it is feasible that some of the losses observed in flow to pumping wells could also occur in flow to an artesian vent.

3.2 General Equations of Flow – A Review

3.2.1 Darcy's Law

In 1856 Henry Darcy published a paper based on experiments with water flowing through a sand-filled column. Using varying pressure heads Darcy observed flow rates and showed that flow through the sand column was directly proportional to pressure head and inversely proportional to the length of media travelled through (Figure 3-1).

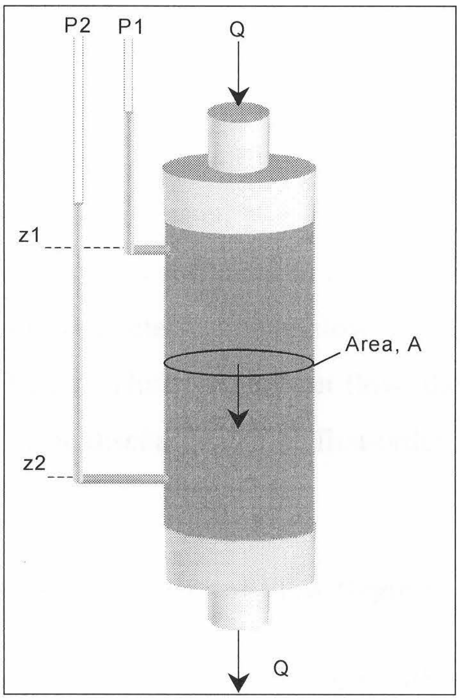


Figure 3-1 Flow through a simple sand column

From these experiments Darcy's law is derived as:

$$Q = kA\frac{dh}{dl} \qquad (3\text{-}1)$$

where:

Q is the flow per unit time (L^3/t)

k is hydraulic conductivity (L/t)

A is the cross sectional area of flow (L^2)

$\frac{dh}{dl}$ is the hydraulic gradient (dimensionless)

k, the hydraulic conductivity, is dependent on the properties of fluid used and can also be represented as:

$$k = \frac{\gamma}{\mu} K \tag{3-2}$$

where:

γ is the unit weight of fluid (ρg) (M/Lt^{-2})

μ is the fluid's dynamic viscosity (M/Lt)

K is the intrinsic permeability of the porous medium and is independent of the fluid passing through (L^2)

Darcy's law, however, is only valid when fluid flow is entirely laminar. The relationship between discharge, Q, and pressure head, h, for a given length, l, is first-order. k is therefore the coefficient of proportionality for the pressure-velocity relationship for completely laminar flow of a fluid through a porous medium (see section 3.2.2). Thus for Darcian flow, the relationship between artesian pressure and spring discharge will be first-order.

3.2.2 Reynolds Number: Indicator of Flow Regime

Laminar flow is defined as fluid moving in layers with viscous shear forces in the fluid dampening any tendencies toward erratic movement. Particles in turbulent flow have erratic motion and tendencies for irreversible energy loss due to the mechanical energy of eddies and vortices (Figure 3-2).

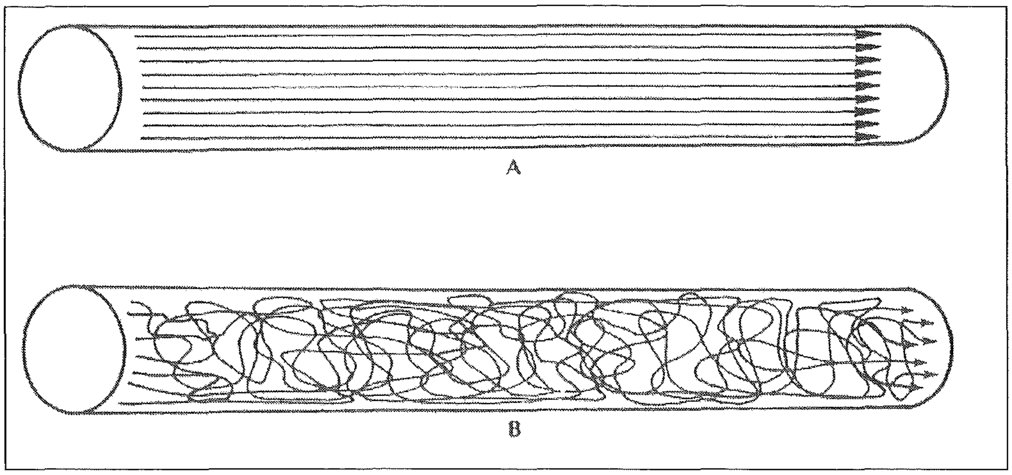


Figure 3-2 Laminar (A) and turbulent (B) flow regimes (Fetter, 1994)

Essentially a ratio of inertia force to viscosity force, the Reynolds number is an indication of turbulence. Although dimensionless the Reynolds number is derived from characteristic fluid flow properties so that different flow situations having the same Reynolds number are dynamically similar, and should therefore perform comparatively.

The Reynolds number is calculated by:

$$R_e = \frac{vl\rho}{\mu} \tag{3-3}$$

where:

v is a characteristic velocity (L/t)

μ is the viscosity (M/Lt)

ρ is the fluid mass density (M/L^3)

l is a characteristic length (L)

At low Reynolds numbers the dominating force is viscosity, and as a consequence energy losses are directly proportional to the average velocity. At high Reynolds numbers, inertia dominates and losses become proportional to the square of the average velocity.

From the above equation it should be noted that Reynolds numbers, and hence the tendency for turbulence, increase when:

- Velocity is high
- There is a large expanse of fluid (allowing more eddies)
- Fluid density is high
- Fluid viscosity is low

A characteristic feature of flow in a porous medium is the gradual transition from laminar to turbulent flow starting at very low, and extending over a wide range of, Reynolds numbers. The smooth transition is due to the tortuous flow path provided by the pore space, with contractions and expansions, and the surface roughness of the porous medium, which favour vortex and eddy formation, and fluid flow disturbance. The transition may be further smoothed by the propagation of turbulent flow from larger pores to smaller ones, and is dependent on the size distribution of the pores in the medium (Idelchik, 1986).

Many investigations, including Williams (1985) and more recently Wahyudi *et al* (2002), have shown that flow through porous media deviates from laminar flow at much lower Reynolds numbers than flow through pipes, where Reynolds numbers up to 2000 may be treated as laminar. Fetter (2001) recommends that Reynolds numbers as low as 10, and ideally less than 1, should only be accepted as true laminar flow.

3.2.3 Non-Darcian Flow

Fluid flow that is not laminar involves complex interactions between particles and the medium through which the fluid is flowing. This deviation of flow from a laminar state, thus invalidating Darcy's law, is termed 'non-Darcian flow'.

As early as 1901, Forchheimer reported a non-linear pressure drop when the flow rate was increased in experiments in packed bed chemical reactors, and suggested the addition of the squared and cubic velocity terms in the Darcy equation.

Fancher and Lewis (1933) studied pressure drop during flow through a large number of unconsolidated and consolidated porous media, and correlated the data using friction and Reynolds numbers with grain diameter as a characteristic length. Again this showed an increased pressure drop at high flow rate greater than that proportional to velocity.

3.2.4 The Bernoulli Equation

The Bernoulli equation shows that the total energy of a flowing fluid is made up of three components: the physical head (potential energy), the energy head (kinetic energy), and pressure head (pressure energy). For incompressible, frictionless flow along a flow line:

$$z + \frac{\rho v^2}{2g} + \frac{P}{\rho g} = constant \qquad (3\text{-}4)$$

where:

z is elevation head (L)

P is fluid pressure (M/Lt^2)

v is fluid velocity (L/t)

ρ is fluid density (M/L^3)

In groundwater flow situations the velocity head is often negligible as velocity is generally low (m/day) and changes in velocity even lower. However, in areas of high velocity flow, such as around well screens and large point source springs, there is potential for velocity head to become a significant factor. The velocity head will increase proportionally to the velocity squared, and cause a corresponding reduction in piezometric pressure, and the relationship between artesian pressure and spring discharge will become non-linear.

Applying the Bernoulli equation to Darcy's sand flow set-up (constant head permeability test) Bernoulli's law fails, because of friction present in the flow system. Bernoulli's equation states that:

$$z_1 + \frac{P_1}{\gamma} + \frac{v_1^{2}}{2g} = z_2 + \frac{P_2}{\gamma} + \frac{v_2^{2}}{2g} \tag{3-5}$$

However, from equation 2-1 a constant discharge though a constant area requires constant velocity. Therefore the velocity terms will cancel and as Z_1 *decreases* to Z_2, P_1 also *decreases* to P_2. The energy lost is due to friction head loss from the interaction of the flowing fluid and the sand particles, or:

$$z_1 + \frac{P_1}{\gamma} + \frac{V_1^{2}}{2g} = z_2 + \frac{P_2}{\gamma} + \frac{V_2^{2}}{2g} + H_{friction} \tag{3-6}$$

One method of determining $H_{friction}$ is to use the Darcy-Weisbach equation.

3.2.5 Darcy-Weisbach Equation

Irreversible energy losses in pipe flow occur due to friction between the fluid and pipe walls. As a consequence, changes in fluid energy from potential to kinetic and back will never be totally elastic, and energy will be lost from the fluid to the pipe and the system environment in form of heat and sound.

The process of energy loss of fluids as they flow through soils is no different to that of flow though pipes. Soil pore space can be viewed as a distinct type of tortuous pipe and hydraulic head will govern flow through soils just as it does in pipes.

The Darcy-Weisbach equation relates head loss, h_l, to diameter and flow velocity by:

$$h_l = f \cdot \frac{l}{d} \cdot \frac{v^2}{2g} \tag{3-7}$$

where

l is the length of pipe (L)

d is the diameter of pipe (L)

v is the average velocity (L/t)

f is a friction factor (dimensionless)

The friction factor, f, is a function of pipe characteristics and flow regime, i.e. the Reynolds number.

At low Reynolds numbers the Darcy-Weisbach equation reduces to the Darcy equation (see section 3.3.1), however at high velocities, and in turbulent flow, energy losses are proportional to the fluid velocity squared, and so turbulent flow will cause the relationship between artesian pressure and spring flow to again be non-linear.

3.3 Flow Regimes

In flow equations not concerned with Darcian flow pressure head loss is a function of the fluid velocity squared. Idelchik, Forchheimer, Darcy-Weisbach (non-laminar) and Bernoulli equations are examples. At very low flows the energy of fluid particles is so low that the dominating force of flow resistance is the fluid shear due to viscosity. The presence of stationary boundaries, i.e. the aquifer matrix, increases the resistance to flow.

From Chapter 2, artesian spring flow consists of three stages:

1. The velocity of water flow in the source aquifer is very low.
2. As flow nears a fissure or pipe in the upper aquitard its velocity will increase proportionally to the area through which the fluid must flow to exit the aquifer.
3. Finally when water enters the fissure, pore space is no longer a controlling condition, and the hydraulic conductivity is likely to be orders of magnitude higher than that of the porous media of the aquifer.

The majority of flow in the source aquifer will be sufficiently low to obey Darcy's law, however as the flow nears a fissure, velocities can become high enough to depart from a laminar regime. Upon exiting the aquifer, the expansion into the comparatively large vent fissure increases the potential for turbulent, swirling, flow.

At low velocities a fluid's energy due to its movement, $v^2/2g$, is very small and low velocity flow is effectively proportional to the hydraulic grade line, with a first-order relationship between pressure head and velocity. By observation of the Bernoulli and the Darcy-Weisbach equations, however, it can be seen that the hydraulic gradient can quickly become complex, with losses proportional to the fluid velocity squared from both energy head and friction losses. This indicates that the relationship between aquifer pressure and spring discharge is very unlikely to be first-order.

3.3.1 Laminar, Low Energy, Flow

At low velocities fluid energy head becomes negligible, collisions between water particles act fully elastically, and flow through the soil will be proportional to the hydraulic grade line associated with the flow system.

Rearranging the Darcy-Weisbach equation yields:

$$\frac{h_f}{l} = \frac{f}{d}\cdot\frac{v^2}{2g} = \text{head loss per unit length, } \frac{dh}{dl}$$

where under laminar conditions (Moody, 1944)

$$f = \frac{64}{R_e} = \frac{64\mu}{vd\rho} \tag{3-8}$$

giving:

$$\frac{h_f}{l} = \frac{64\mu v}{d^2\rho} \tag{3-9}$$

Thus the hydraulic gradient will be proportional to the velocity, and so plotting aquifer pressure change against spring discharge will yield a first-order relationship (Darcy's Law).

In order for laminar flow through a porous medium to exist Reynolds numbers must be less than 10, and ideally less than 1. In a gravel aquifer with mean gravel diameter 10 mm, the maximum particle velocity for valid Darcian flow of 15°C water, with a pore size of approximately half the grain size is:

$$v = \frac{R_e \mu}{\rho l}$$

$$v = \frac{1 \times 1.140 \times 10^{-3}}{999.10 \times 0.005} \quad \frac{kg/m \cdot s}{kg/m^3 \times m/s}$$

$$= 0.0002 \text{ m/s}$$

Therefore from equation 2-1, for every 1 l/s of discharge, the flow area must be in excess of 5 m^2 (negating the effects of porosity). It is therefore very unlikely that flow will remain laminar as it passes from the aquifer through a spring fissure and vent and into the stream. In the case of pressure loss being entirely due entirely to laminar losses, however, then halving the initial driving head will result in a spring discharge exactly half of the initial flow (Figure 3-3).

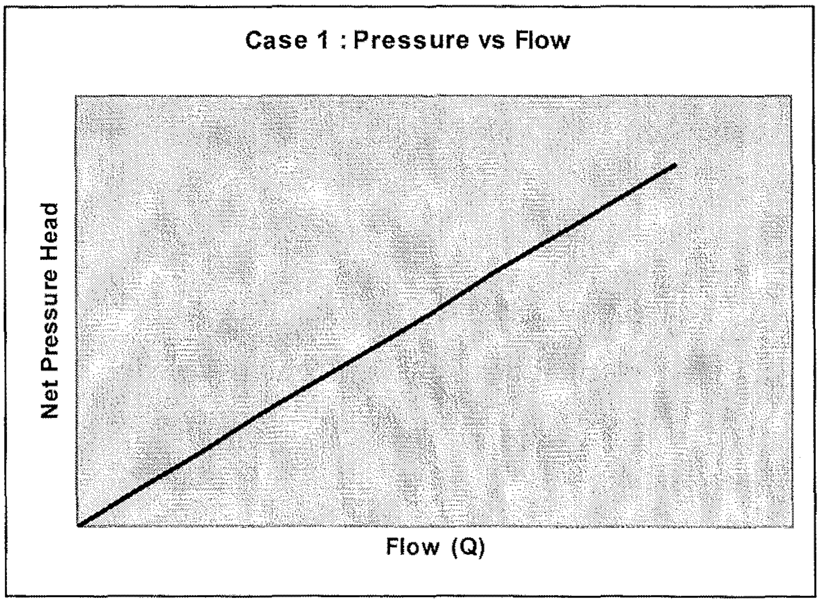


Figure 3-3 Plot of first-order pressure-flow relationship

3.3.2 Turbulent, High Energy, Flow

At high Reynolds numbers (>>10) turbulence dominates the flow regime. Losses in turbulent flow will be proportional to the fluid velocity squared, and as a consequence the relationship of spring discharge to pressure head will be non-linear (Figure 3-4).

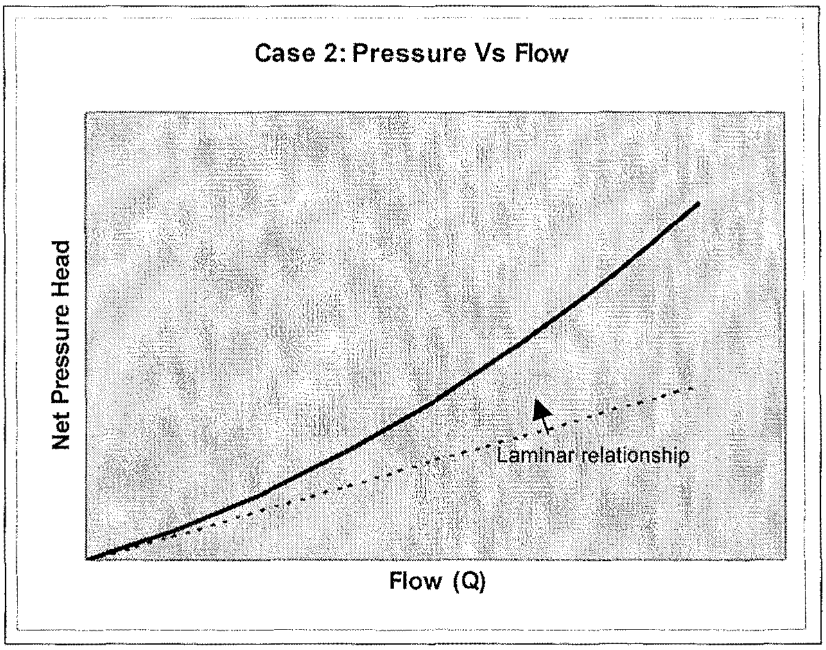


Figure 3-4 Plot of high energy pressure-flow relationship

As in the case of well efficiency, if flow becomes turbulent, the total loss in the system will comprise loss due to laminar flow though the aquifer and the loss as the fluid travels as turbulent flow. Jacob (1947) represented this as:

$$h_f = bQ + cQ^2 \qquad (3\text{-}10)$$

where:

b is the first-order loss coefficient for Darcian flow

c is the turbulent loss coefficient for non-Darcian flow

Q is the flow from the spring (L^3/t)

3.3.3 Implications of Turbulent Flow

The effect of a non-linear relationship between artesian pressure and spring discharge would serve to buffer spring performance against aquifer pressure change. For a reduction of artesian pressure by half the resulting performance decrease in spring discharge will be reduced by a factor less than half. Conversely an increase in artesian pressure will have a reduced effect upon spring discharge and theoretical maximum as dynamic head loss approaches driving artesian pressure head.

3.4 Groundwater Flow Models

Mathematical groundwater models were used in order to estimate pressure changes induced at the spring by water abstraction using measured near-spring drawdowns. A number of models for groundwater flow to a well in a confined aquifer exist, but while theoretically sound, some do have limitations in accurately simulating field conditions (Kruseman and De Ridder, 1990) and have sensitive variables resulting in sometimes inconsistent aquifer parameters and non-unique solutions. Therefore, only three models were used for simplicity and consistency:

- Thiem (1906), which utilizes steady state flow to determine transmissivity;

- Theis (1935), where aquifer parameters for transmissivity and storativity are required; and
- Hantush-Jacob (1955), where a term for leakage is also included to assist in modelling semi-confined conditions.

These models are discussed in detail in Appendix C.

The assumption is made that the material constituting the source aquifers is effectively homogenous and isotropic, with hydraulic conductivities in the x, y and z directions all approximately similar (i.e. that $K_x = K_y = K_z$). This assumption is often not an accurate field description as the layered nature of the sediments will reduce the average vertical conductivity, and preferential flows down-gradient will alter conductivities in the x and y directions. This assumption is, however, a requirement needed in order to apply present analytical groundwater models, and as a consequence accuracy in model predictions could be restricted. For the purposes of this research, careful control of the pumping schedules attempted to minimise the impact of model assumptions not being met.

Further assumptions required by the groundwater flow models (Kruseman and De Ridder, 1990) are that:

- The aquifer has a seemingly infinite areal extent.
- The aquifer is of uniform thickness over the area influenced by the test.
- That prior to pumping, the piezometric surface is horizontal over the area that will be influenced by the test.
- The pumping well penetrates the entire thickness of the aquifer, and thus receives water by horizontal flow.
- The water removed from storage is discharged instantaneously with decline of head.

Storage in the well can be neglected.

3.5 Chapter Synthesis

For Darcian flow the relationship between artesian pressure and spring discharge will be first-order and any reduction in artesian pressure of a source aquifer will have a direct, first-order effect, on spring discharge. For high velocity flow the fluid energy associated with velocity head will become significant, the flow regime will become turbulent, and the relationship between artesian pressure and spring discharge will become non-linear.

The consequence of a non-linear relationship between artesian pressure and spring discharge is that dynamic losses in the spring system will buffer the effect of artesian pressure reduction because a reduction in pressure head will give a disproportionate reduction in dynamic head loss. Preliminary theoretical analysis of groundwater flow to a spring system indicates that turbulent flow is likely to be present, indicating that a non-linear relationship between artesian pressure and spring discharge should exist.

4 Data Acquisition

4.1 Introduction

This chapter describes the test sites, and testing procedures, that were used to obtain empirical data to compare with the hypotheses proposed for both groundwater flow to an artesian spring, and the relationships between artesian pressure and artesian spring discharge. Two sites, one at Brookside and the second at Halswell, were used for testing. The two sites differ in hydrogeological conditions and spring morphologies, with hydrogeological variation sought after to ensure that the artesian spring models developed could be more confidently applied throughout Canterbury, and to other gravel-based artesian spring systems.

The artesian springs at Brookside are driven by relatively low artesian pressures occurring with a thinner confining layer than those at Halswell. The primary test site at Brookside consists of a swarm of vents in a streambed, whereas the Halswell springs are large discrete vents, driven by much higher artesian pressures. Data collection involved obtaining information on:

- Groundwater pressure around the springs.
- Aquifer response to pumping.
- Spring/stream discharge.

4.2 Case Study 1 – Brookside

4.2.1 Introduction

The Brookside site was chosen as aquifer parameters had already been calculated and documented via aquifer testing by Environment Canterbury (Ettema and Smith, 2001). The close proximity of a stream to the pumping well and the relatively shallow well depth suggested that spring/stream depletion may be observed during abstraction.

Groundwater levels at the test site indicate sub-artesian aquifer conditions. The water levels are not above ground level, however the observed springs show artesian characteristics with water actively bubbling up through the silty streambed. This is reinforced by the observed gains in stream flow at discrete locations as it moves downstream, indicating localised interaction between the flowing stream and groundwater.

4.2.2 Site Location

The Brookside test site is located on the property of Mr Ian Odell of Selwyn Lake Rd, Brookside (Figure 4-1). The test site comprises a dairy farm containing a spring-fed stream that begins on site and gains at a number of points downstream before joining a neighbouring stream and finally discharging into the Selwyn River. Previous testing had been carried out on well M36/3548 at the site (Ettema and Smith, 2001; Smith, 2002), an irrigation well 158 mm in diameter and just over 13 m deep, using a surface centrifugal pump for abstraction. At present the well supplies water for dairy irrigation during the summer. Several unused wells (Table 4-2) as well as a domestic supply well are available for water level data collection.

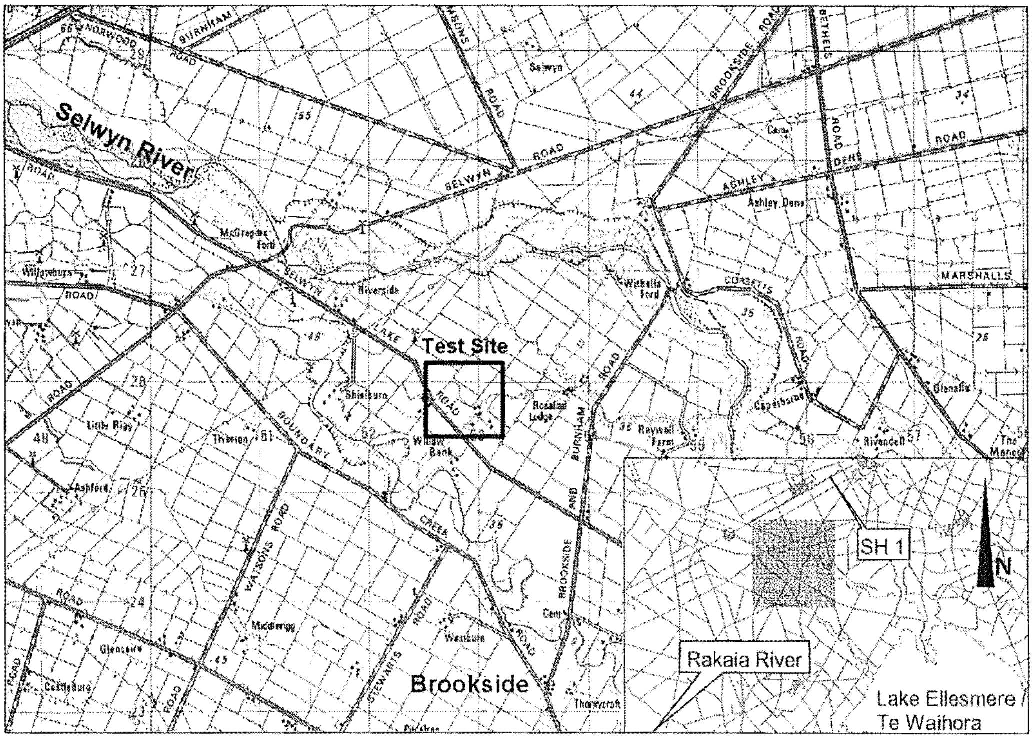


Figure 4-1 Brookside study area location map

4.2.3 Site Hydrogeology

The test site is located between the Selwyn and Irwell Rivers. The site is located just downstream of where the Selwyn River deviates from its general southeast flow direction to flow east for 4-5 km before reverting back to its usual flow direction (Figure 4-1). This change in river course provides a mechanism for water to flow and recharge the gravels forming the sub-artesian aquifer to the south (Figure 4-2). Hand auger holes at the test site revealed stiff plastic blue-grey silty clay, with veins of very fine orange-brown sand, to an average depth of around 2 m followed by a conspicuous change in geology to free running gravels and sand which limited the hand boring investigation. This confining silty clay was encountered at a similar depth over the entire test site and towards the Irwell River, although it is occasionally overlain by gravels just below the topsoil towards the east (down gradient).

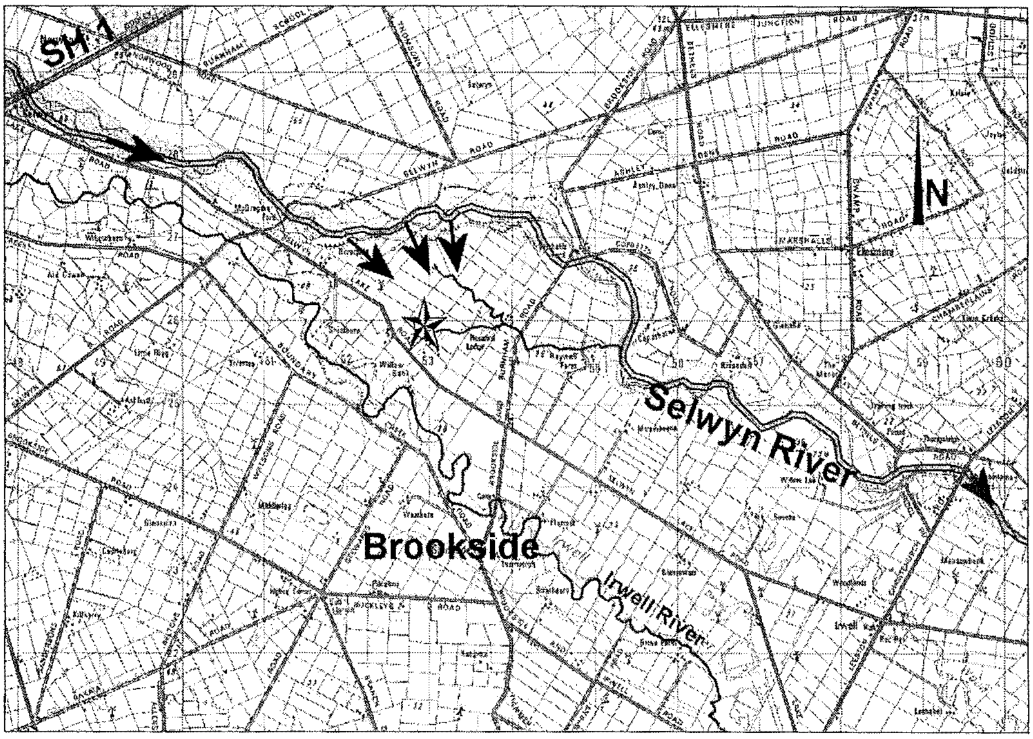


Figure 4-2 Brookside aquifer recharge

Groundwater levels in wells onsite are 1 to 1.5 m below ground level - above the confining layer boundary and streambed levels, but not above general ground level.

Only one existing drilling log was available for the site, that of the new domestic well M36/6836 (adjacent to the old domestic well M36/3547). The next closest available was some 850 m away, and too distant to be of use for realistic correlation. A total of eight logs existed within 1 km of the test site, however the well data was only of limited use to aid in the understanding of the aquifer stratigraphy of the test area. In general the aquifers are made up of free running sandy gravels separated by lenses of silt. The upper aquifer is relatively extensive and is probably in the order of tens of metres thick.

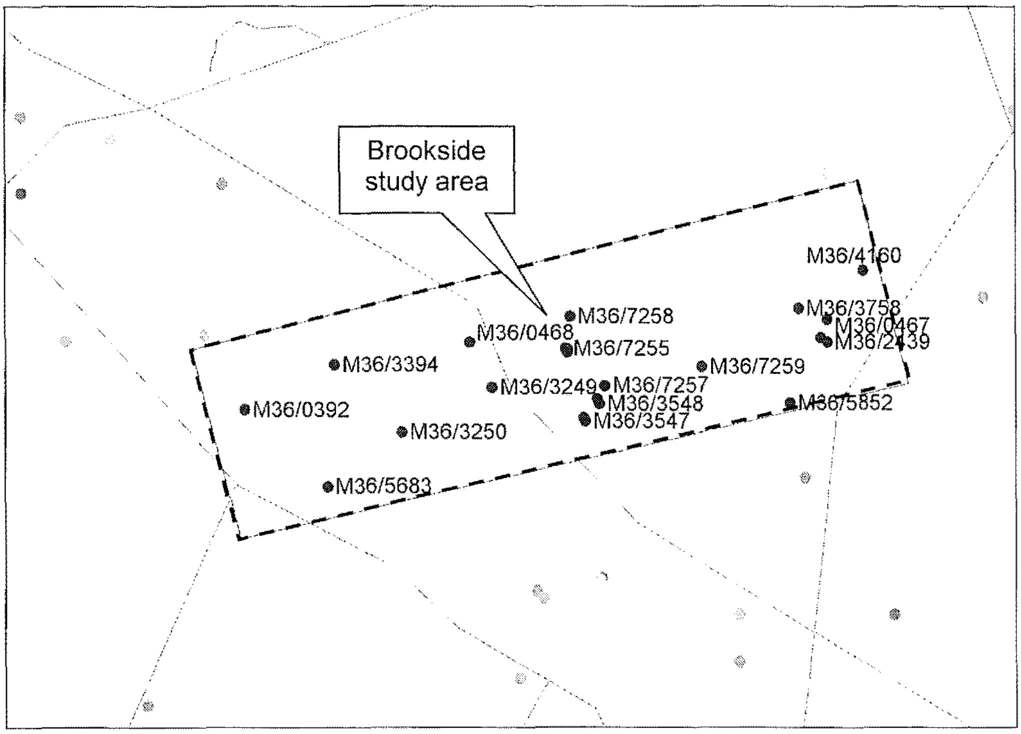


Figure 4-3 Brookside cross-section well locations

The geology of the area encompassing the study site is summarized in Figure 4-4. The data used are sourced from the drilling logs of previously installed wells shown in Figure 4-3, obtained from Environment Canterbury's Wells Database, as well as data gathered during new well installation and hand augering on site.

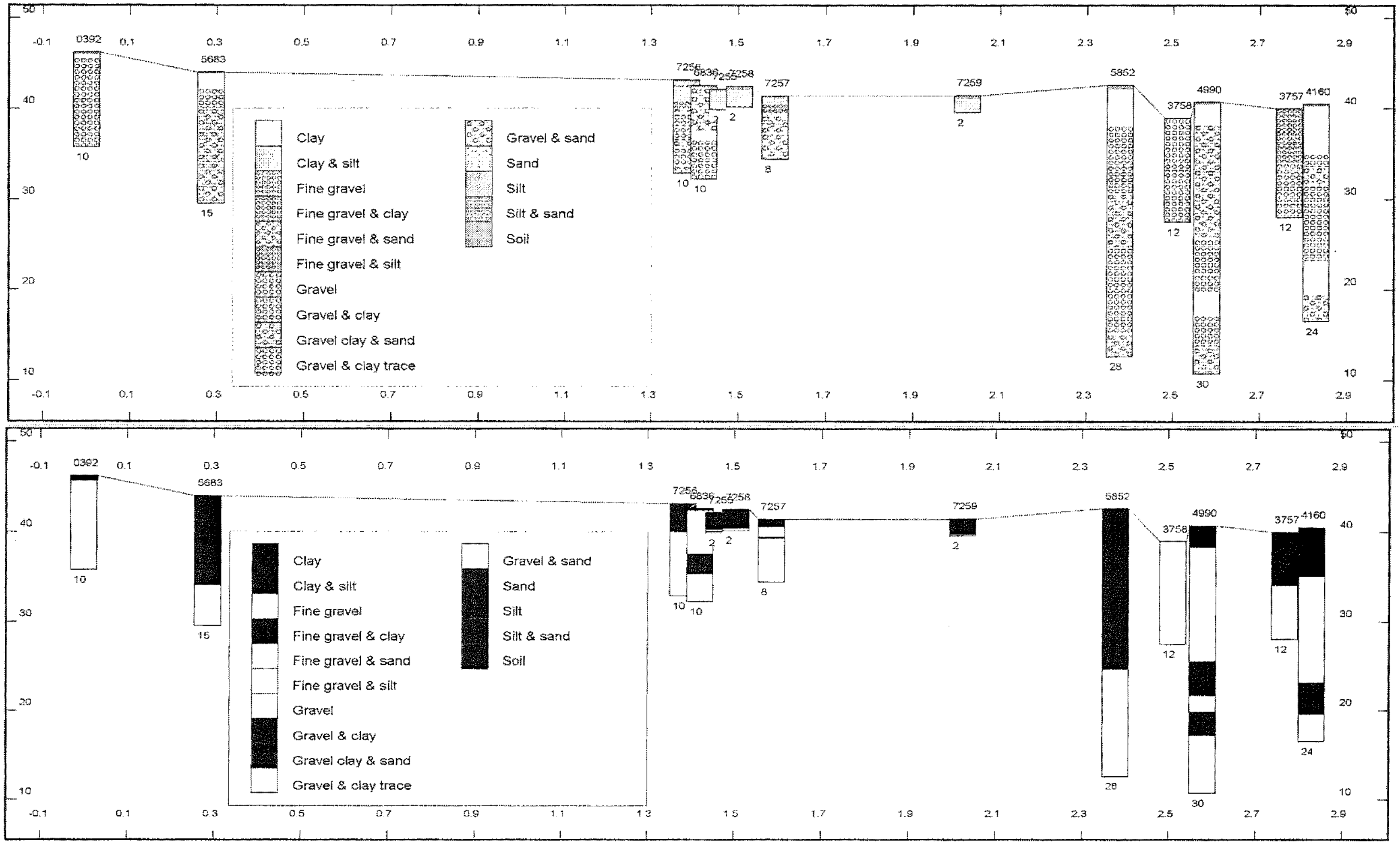


Figure 4-4 Brookside cross-sections, the lower showing simplified aquifers (white)/aquitard (black) classification

The drilling log of M36/6836 indicates a clay layer between 5 and 6 m below ground, suggesting that an aquitard may exist between well M36/3548 and the spring areas. The information in the drilling log of M36/6836 is not consistent with that observed onsite. Other excavations in the local area encountered clay before entering an aquifer or water table, and no other clay or confining layers at similar depths have been recorded. Two new wells were drilled by cable tool to verify the existence of the clay layer, however neither well, drilled to 11 and 7 m, encountered any clay layer as indicated by the existing drilling log (see Appendix D for the drilling logs). It is concluded that the well was logged incorrectly as a locally defined clay layer of 1 m seems unlikely. The clay layer at the surface may have been omitted from the log due to previous construction disturbance in the area. Observed responses in wells M36/7002, M36/3547 and M36/7003 from Environment Canterbury's testing (2001 and 2002) suggest that all wells are screened in the pumped aquifer.

4.2.4 On Site Springs

The springs on site flow from a sandy gravel aquifer, through fissures in the silts covering the streambed ranging from a few centimetres to over a metre in depth. Occasionally gravel extends to the streambed, with very little silt cover where springs emerge. Inter-spring reaches are generally composed of a more substantial, very firm blue-grey clay of low permeability that restricts groundwater – surface water interaction.

The mapped springs at Brookside are M36/5796, M36/7331, M36/7332 and M36/7333 shown in Figure 4-5 with details in Appendix F.

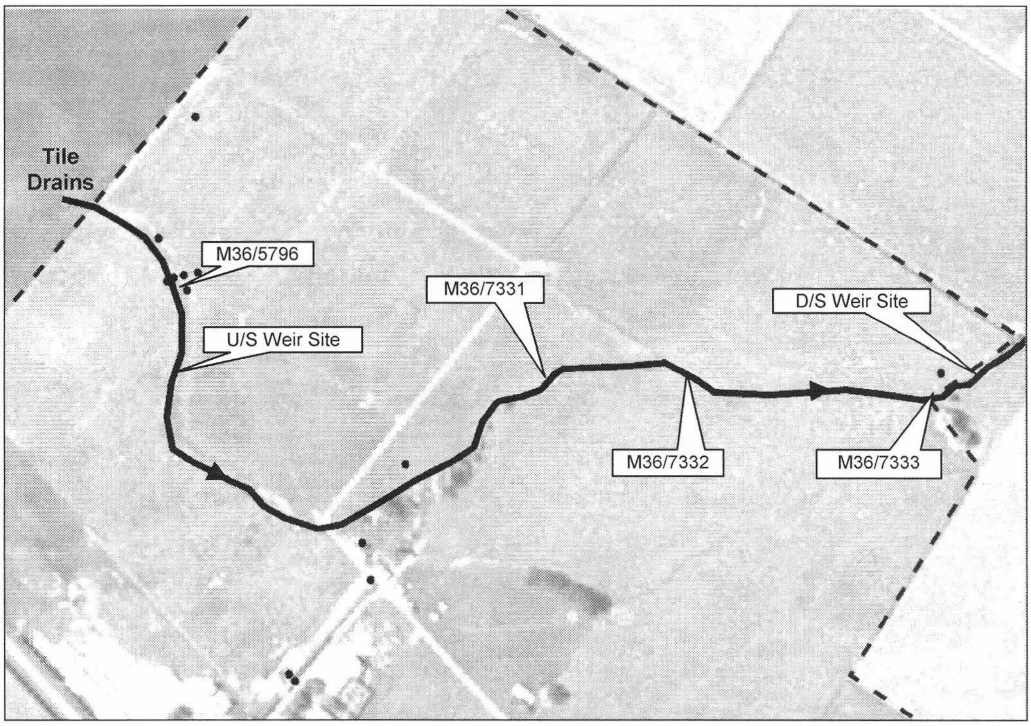


Figure 4-5 Brookside spring locations (black dots represent wells)

M36/5796 has a 'swarm' morphology with a number of small vents occurring along a stretch of streambed 80 m long. These small vents are generally less than 20 mm in diameter, flowing through gravels. M36/5796 also contains two larger spring vents around 80mm in diameter and extending down for more than one metre. The change in vent size represents a change in the fissure geology from gravel to mud and silt. The average total discharge for spring area M36/5796 during the investigation was 34 l/s.

M36/7331 is a point source issuing from the stream bank 400 m downstream from M36/5796. The point of discharge is approximately 0.5 m above the streambed and the spring discharge averaged 8 l/s. Spring area M36/7332 consists of a few small vents. Some gas bubbles, effervescence of dissolved nitrogen and carbon dioxide, can be observed escaping on occasion, however based on gauging data the spring contribution is less than 1 l/s. Spring area M36/7333 appeared to be inactive during the study.

Minor flow gains in the stream from seeps unable to be specifically located between the two weirs is a further 7 l/s, bringing the total average discharge of the stream within the study area to 50 l/s for the duration of this study.

Spring Number	mEasting	mNorthing	Ave Discharge (L/s)
M36/5796	2452807	5725985	34
M36/7331	2453077	5725869	8

Table 4-1 Brookside study main spring locations and discharge

4.2.5 Testing

Testing at the Brookside site was carried out in three stages: the first was primarily as a test of interference monitoring techniques and equipment; the second used the on-site farm well and pump to induce abstraction effects; and the third used Environment Canterbury's surface pump and a new well installed beside the main spring area to produce extreme spring depletion conditions.

4.2.5.1 Test Set-up

The test set-up consisted of two V-notch weir sites, and a number of observation wells. The observation wells were a mix of three existing wells, two newly drilled wells, and numerous hand drilled observation piezometers (Figure 4-6 and Table 4-2).

Self contained pressure transducer recorders called 'Divers' were employed in observation wells two days prior to the testing period, and were supplemented with manual groundwater level readings. An acoustic Doppler flow meter was employed on the pumping well at various times to measure abstraction rates (see Appendix I).

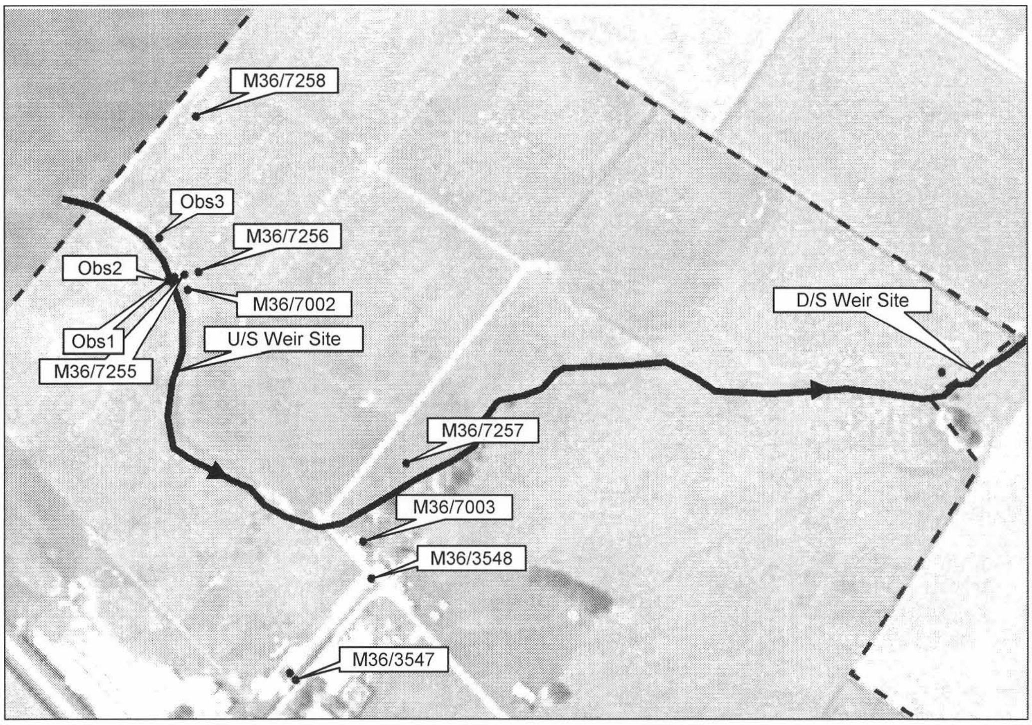


Figure 4-6 Brookside site set-up and well locations

The V-notch weirs were installed, each with a float-type NIWA ‘hydrologger’ water level recorder. One weir was just below spring M36/5796 and the second weir was sited downstream of spring area M36/7333, 495 m away from well M36/3548, on a firm clay streambed with no or very little gains to stream flow. The weirs were levelled to within 1 mm and the resolution of the water level recorders was 1 mm.

Well Number	Description	Depth (m)	Rel Height (top of casing) (m)	mEasting	mNorthing
M36/3548	Pump	13.0	N/A	2452976	5725727
M36/7003	Old Dairy	5.5	-0.06	2452966	5725749
M36/3547	Domestic	8.2	0.00	2452912	5725650
M36/7002	Spring well	2.5	-0.417	2452832	5725956
M36/7256	New #1	10.2	0.714	2452832	5725971
M36/7257	New #2	7.5	-0.053	2452999	5725808
M36/7258	Hand Well	2.2	1.803	2452846	5726114
M36/7255	Strm Bank	2.25	-0.497	2452824	5725972
OBS1	Spring	1.5	-0.437	10 m from	M36/7256
OBS2	Stream	1.5	-0.867	13.5 m from	M36/7256
OBS3	Upstream	1.0	-0.737	33.2 m from	M36/7256

Table 4-2 Brookside well data

Background water level data was taken from wells M36/0338 (4.0 m deep) and M36/0419 (12.2 m deep), 2200 m and 2400 m from M36/3548 respectively. These observation wells are considered to be in the source aquifer.

4.2.5.2 Stage One - Preliminary Testing, February 2002

The objectives of the preliminary testing, carried out between 20 and 23 February 2002, were to determine aquifer parameters at the site, and to test flow depletion monitoring techniques. Water was pumped from M36/3548 at an average rate of 24 l/s and was discharged through the farm irrigation system and applied to fields 800 m to the southeast (downstream). This testing was carried out prior to irrigation commencing in the Brookside area.

Groundwater levels were recorded in three observation wells namely: M36/7002 (shallow pipe in spring area), M36/7003 (behind old dairy shed) and M36/3547 (the old decommissioned domestic well beside the new domestic well M36/6836), being 281.0, 96.8, and 26.0 m from the pumping well respectively.

The aquifer testing was carried out in a week with stable meteorological conditions, with no rain and no severe atmospheric pressure changes. Water levels decreased in both background wells over the testing period, part of a general regional decrease throughout February and March 2002 (see Appendix J).

Initially stream flow gaugings were carried out before and during testing, and seepage meters were installed in three locations in the streambed the week before testing to allow them to settle and stabilise. Mixed results were obtained from the seepage meter readings and flow gaugings while pumping was underway, and these methods proved to be inadequate in indicating changes in spring flow. A V-notch weir and 'hydrologger' water level recorder were installed instead to monitor stream flow to a more accurate degree.

Stream flow was monitored for the majority of the irrigation season, from 25 February until late March/early April 2002 when irrigation ceased. Well M36/3548 stopped pumping between 1 and 5 March allowing groundwater levels to recover, and then decline again when pumping resumed. A response was observed in stream flow, in the form of a 4 l/s increase, upon pump shutdown on 1 March. When pumping resumed a corresponding drop in stream flow could also be readily determined (Figure 4-7).

A second recovery period when the irrigation season finished was also recorded and a similar stream response observed (Figure 4-8), however other irrigators in the area also shut down at a similar time resulting in an increase in general water levels (Appendix J) that may have distorted the flow recovery. The response in stream flow is sufficiently rapid that flow spikes corresponding to short breaks in pumping, while irrigation equipment was moved, can be observed.

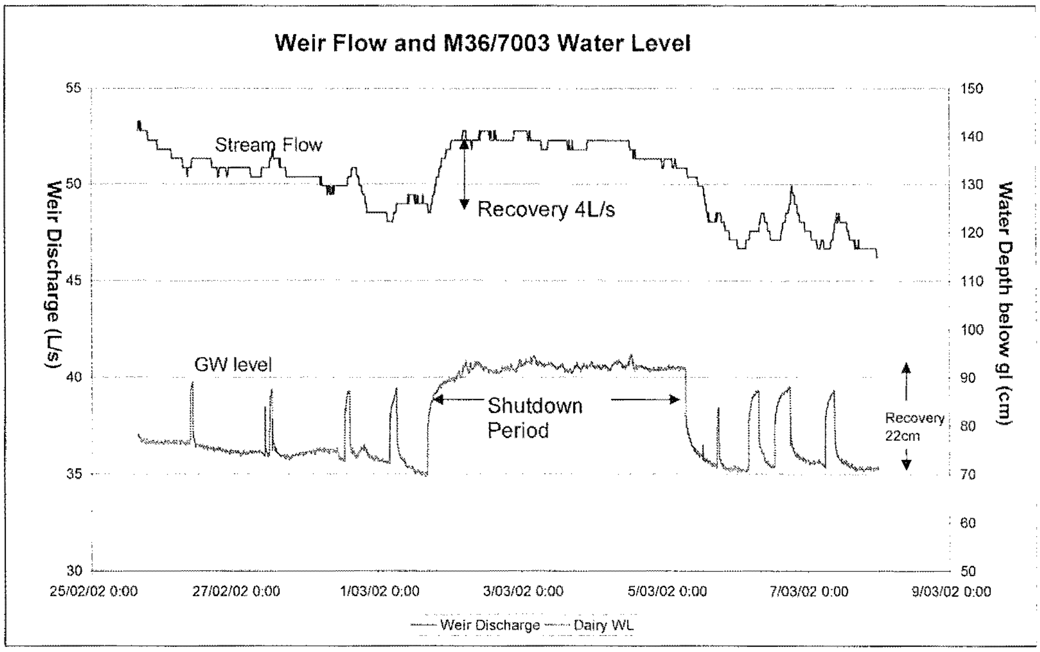


Figure 4-7 Brookside response to cessation of pumping

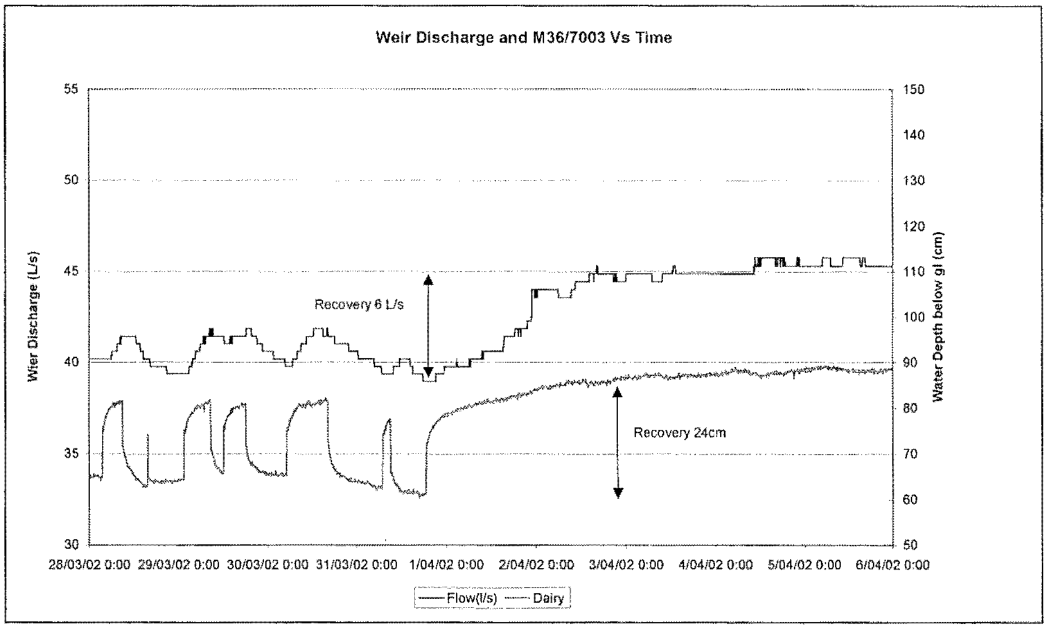


Figure 4-8 Brookside spring response to end of irrigation season

4.2.5.3 Stage Two - Pumping from M36/3548, October 2002

This second stage of testing, in October 2002, used the dairy irrigation pump to abstract and discharge water from M36/3548 into a ditch that feeds the stream downstream of the lower weir. The purpose of this stage of testing was to induce a change in aquifer pressure at all spring sites and observe the stream discharge responses. This test utilised observation wells in order to check drawdown responses and confirm previous estimations of aquifer parameters.

Pumping of M36/3548 was carried out at the rates and times outlined in Table 4-3. the observed responses from groundwater and spring flow due to pumping are shown in Figures 4-9 and 4-10

ON	Ave. Rate (l/s)	OFF	Ave. Rate (l/s)
7/10/2002 16:07	11.1	8/10/2002 15:49	9.9
9/10/2002 14:20	16.9	10/10/2002 10:41	17.0
12/10/2002 13:19	22.7	13/10/2002 13:15	24.5
15/10/2002 13:06	8.8	16/10/2002 13:55	9.1
16/10/2002 13:56	30.3	17/10/2002 12:46	23.6

Table 4-3 Brookside, M36/3548 test data

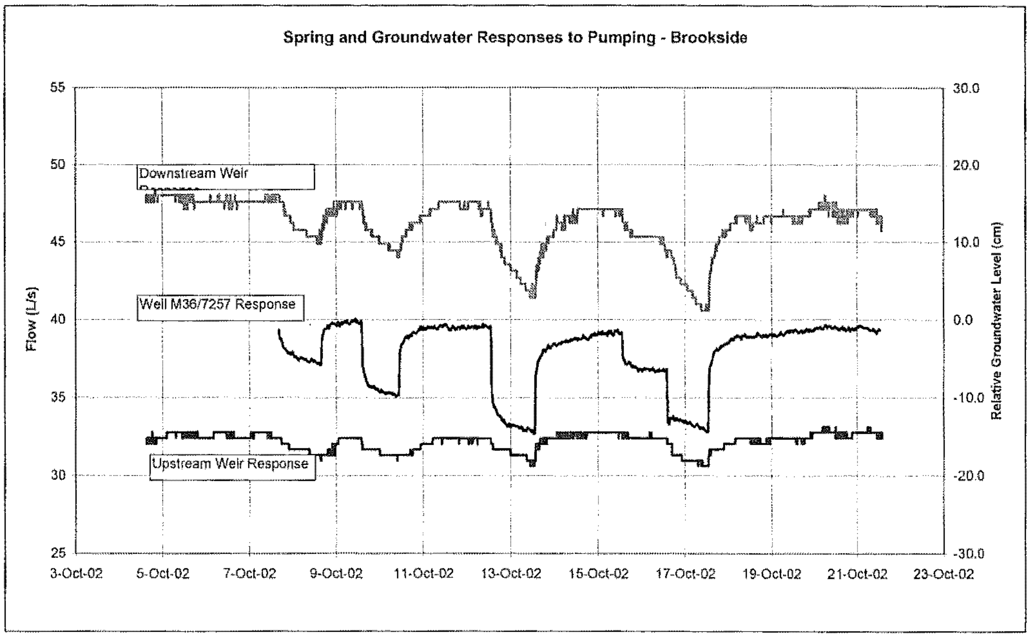


Figure 4-9 Brookside spring and groundwater response to stage two pumping

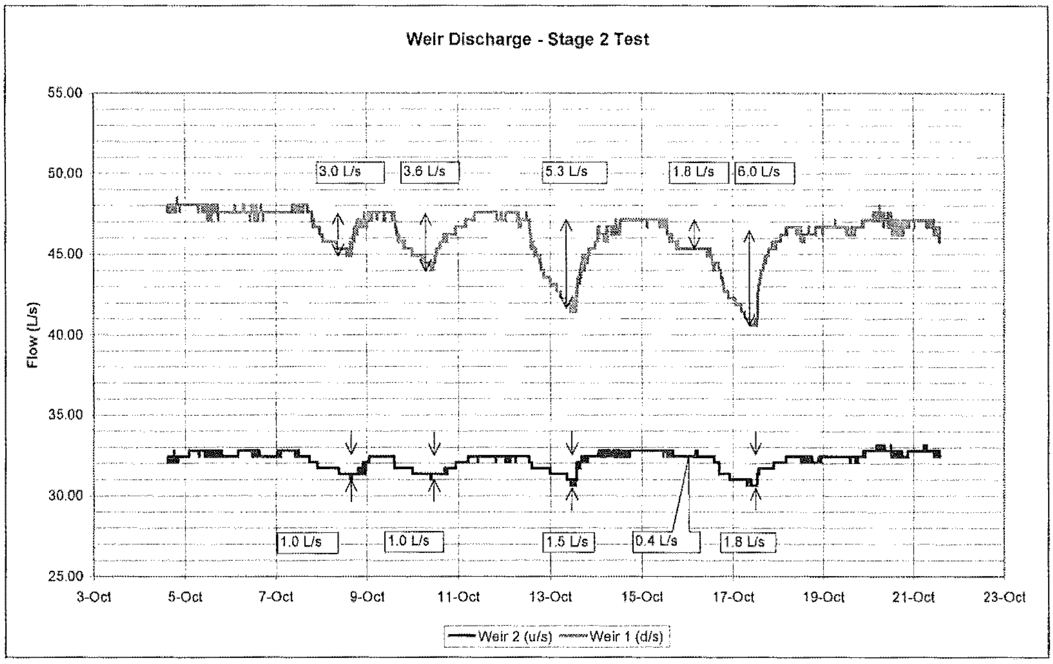


Figure 4-10 Brookside weir response to stage two pumping

Aquifer response data can be found in Appendix L.

4.2.5.4 Stage Three – Environment Canterbury Pump, November 2002

The final stage of testing involved abstraction from well M36/7256 and discharge into the stream downstream of the upstream weir. Water levels were observed in OBS1, 2, 3 and M36/7255. This stage of testing was used to determine aquifer parameters close to the upper spring, M36/5796, and to compare drawdown data with stage two.

Pumping of M36/7256 was carried out at the following rates and times.

Date	ON	Rate l/s	OFF	Rate l/s
31-10-2002	12:00	10.7	16:52	11.2
4-11-2002	10:30	4.2	16:27	4.0
5-11-2002	11:00	9.0	15:58	9.0
8-11-2002	11:49	8.0	16:03	7.9
9-11-2002	11:44	5.4	16:31	5.5
11-11-2002	10:37	11.9	16:58	12.0

Table 4-4 Brookside, M36/7256 test data

The limited maximum output rate of well M36/7256 restricted the range of drawdown conditions that could be induced, however observable changes in stream flow were recorded (Figures 4-11 and 4-12). See Appendix L for aquifer response data.

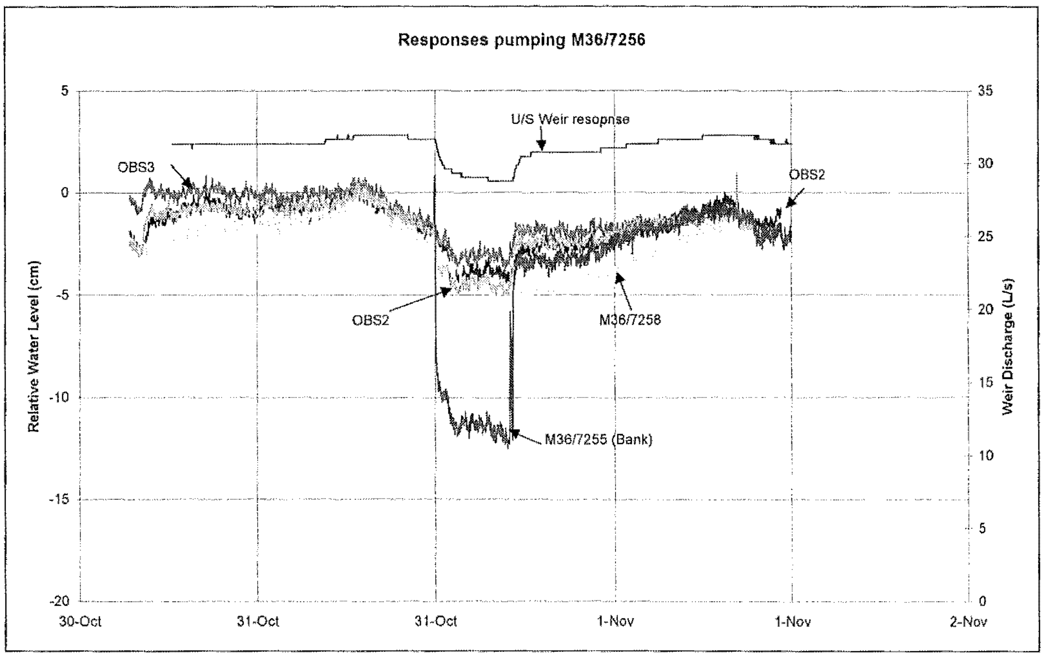


Figure 4-11 Brookside aquifer and spring area M36/5796 response to pumping

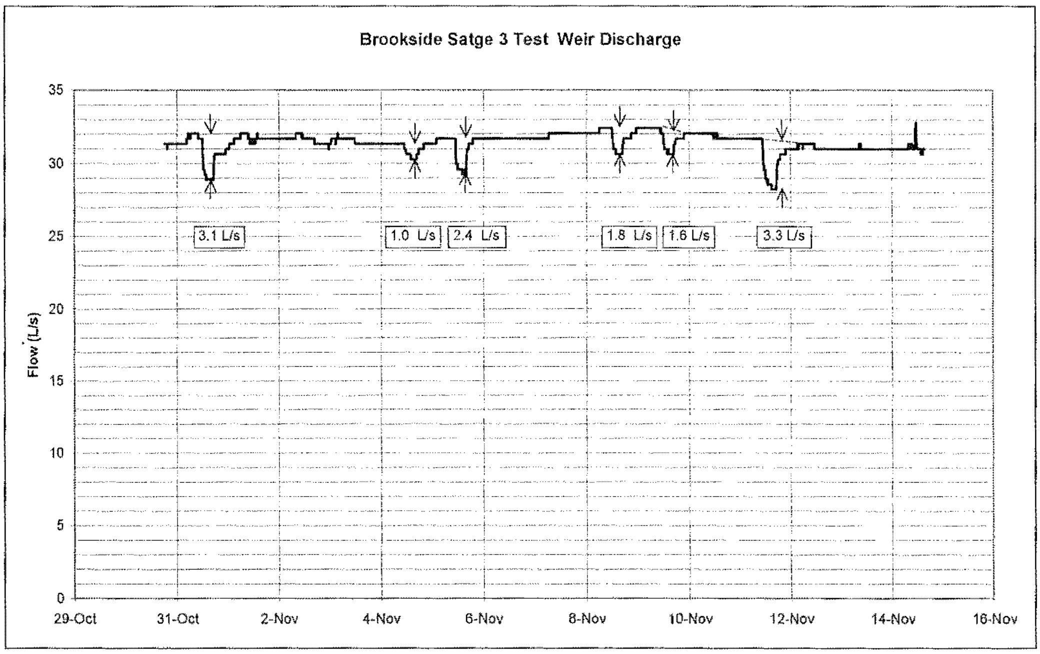


Figure 4-12 Brookside spring area M36/5796 response to stage three pumping

4.2.6 Barometric Efficiency

Large atmospheric pressure changes (the equivalent of up to 70cm of water pressure) occurred during aquifer testing, however plots of groundwater levels vs atmospheric pressure do not indicate any significant relationship (Appendix K). It is therefore concluded that the shallow aquifer at Brookside has a low barometric efficiency and that the effects of air pressure change have a negligible influence on groundwater levels.

4.2.7 Aquifer Parameters

Stage one testing at the Brookside site indicated that the water source that M36/3548 exploits is a semi-confined aquifer with characteristics such that a single model is not sufficient to explain or predict groundwater reactions to abstraction at differing static groundwater pressures (Smith, 2002). As the aquifer parameters for the aquifer vary with differing groundwater conditions, the parameters were recalculated and compared to previous results (Table 4-5).

Aquifer test responses from the pumping of well M36/7256 (stage two), indicate that the hydraulic conductivity of the aquifer increases significantly close to the active spring area M36/5796, with similar responses from all observation wells located near the springs regardless of distance (Figure 4-11). This, along with the close proximity of well M36/7255, invalidates the aquifer model assumptions and the final parameters are only a broad estimate of the true aquifer parameters. However, as the pumping times are similar, the ratio of maximum drawdown will be directly proportional to the pumping rate and a relationship between aquifer pressure change and spring discharge should still be obtained.

Test	Analysis	T (m^2/day)	S	B (m)
Stage One	Theis	5300	0.03	N/A
	Hantush - Jacob	4500	0.03	492
Stage Two	Theis	8800	0.003	N/A
	Hantush - Jacob	4800	0.02	457
Stage Three[1]	Theis	5920	0.097	N/A
	Hantush - Jacob	1430	0.1	11

Table 4-5 Brookside aquifer parameters

The most appropriate model for spring drawdown testing (stages two and three) was the Hantush-Jacob model, and detailed analysis is included in Appendix M.

[1] Estimate of parameters unlikely to representative of aquifer due to model assumptions not being met.

4.3 Case Study 2 – Halswell

4.3.1 Introduction

The Halswell test site contains a number of important characteristics making it potentially the most suitable site considered. It is located in an area of high artesian pressure and contains a number of permanent artesian springs. The spring vents tend to be well defined and occur in discrete reaches of streambed, with generally only one or two vents occurring at any one location. The morphology of a number of vents allows for relatively simple measurement of discharge, and the lack of irrigators or large water users in the area reduces the potential for abstraction interference.

4.3.2 Site Location

The site is located on Cashmere Road, at the mouth of the Hoon Hay Valley (Figure 4-13). The test site comprises a deer farm containing tributaries of Cashmere Stream, itself a tributary of the Heathcote River. A number of large artesian vents occur between Sutherlands Road and Cashmere Road feeding into the tributaries, and these are sourced entirely from groundwater.

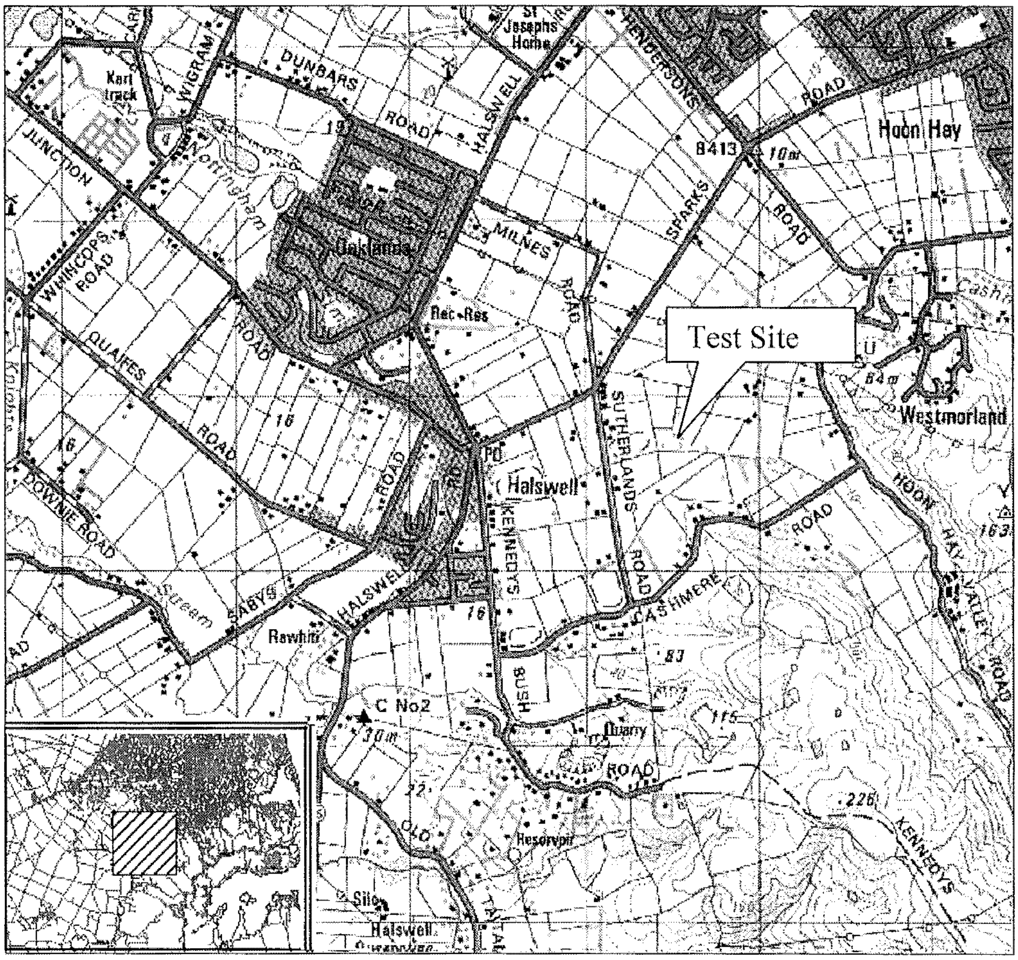


Figure 4-13 Halswell test site location

4.3.3 Site Hydrogeology

The shallow hydrogeology of the area comprises Riccarton Gravels, the shallow aquifer, overlain by Christchurch Formation creating the confining layer. No water table, or unconfined, aquifer is present.

The shallow aquifer is true artesian, with water levels over a metre above ground level in places although groundwater levels reduce toward spring vents. The presence of gas bubble indicates that the water has been pressurised long enough to allow gases to be dissolved, and effervesce upon exiting the aquifer via the spring as the pressure is reduced.

The closest existing well to the test site was M36/1938 some 145 m away. The type of soil, hydrogeology, and farming of the area is such that no large irrigation projects presently operate here, and as a consequence there are few existing wells on or near the test site. The Environment Canterbury Wells Database records all wells in the area as being driven pipes, and as a result little detail was known of the local hydrogeology. Analysis of the depths of wells installed in the surrounding area indicated that around a third of the wells in a 1 km radius of the site were installed to a depth no greater than 12 m (Figure 4-14), assuming that the wells were installed well below the upper confining geology, then depth to gravel was estimated to be 5-10 m and installation of new temporary observation wells and production wells was proposed.

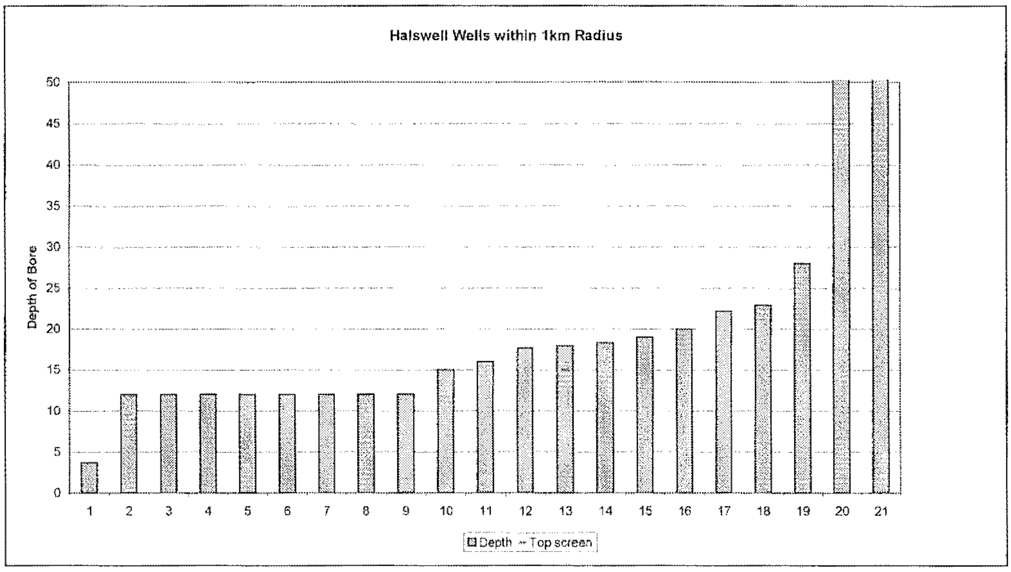


Figure 4-14 Depth of wells around Halswell site

Well installation revealed that, around the springs at least, depth to gravel was between 6 and 7 m (Appendix D). As a result of limited information obtained from the well installation, a sixth well was drilled to a depth of 5 m using a hand auger. Care was taken to ensure that any penetration of the aquifer would not result in the flooding of the surrounding farmland by drilling inside a temporary PVC casing, the top of which was retained above the expected piezometric level. The hand drilling did not penetrate the aquifer and no obvious internal water table was encountered in the aquitard. The hand drilling (log M36/7254, Appendix D) revealed that the aquitard is made up of light grey clayey silts intermixed with layers of darker grey fine sandy clay. The lenses of sandy clay were obviously more permeable with samples having a 'sloppy' appearance and proving difficult to retrieve from the borehole.

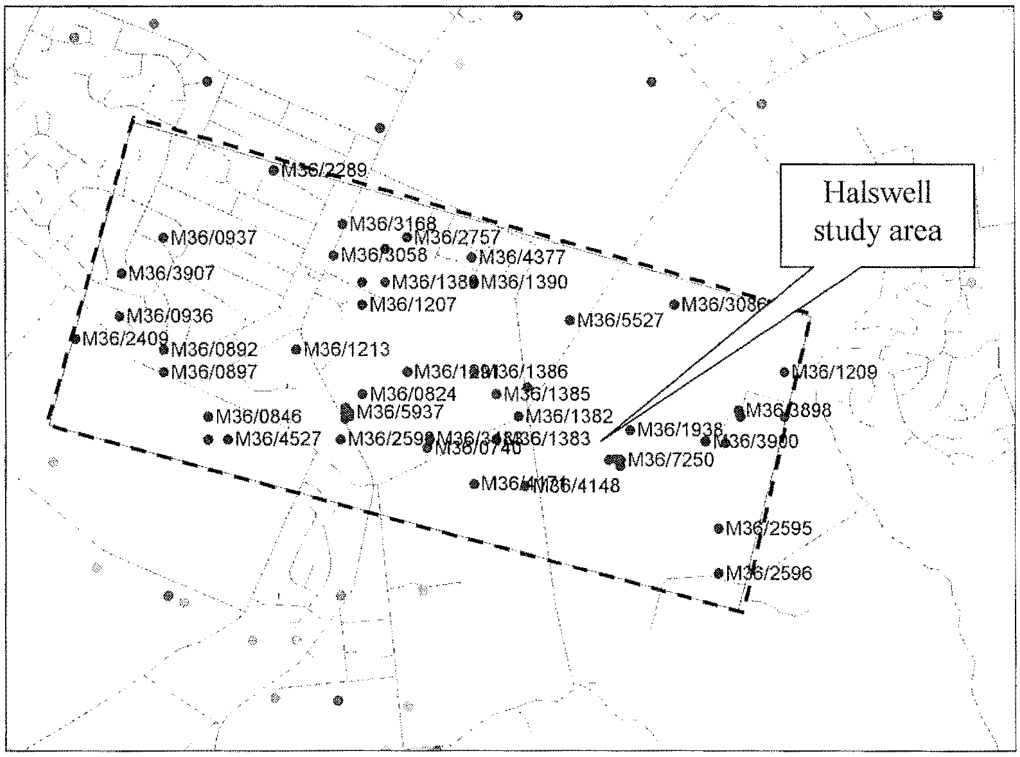


Figure 4-15 Halswell cross-section well location

The geology of the land encompassing the study area is summarized in Figure 4-16. The data used is sourced from the drilling logs of previously installed wells shown in Figure 4-15 obtained from Environment Canterbury's Wells Database, as well as data gathered during temporary well installation and hand drilling.

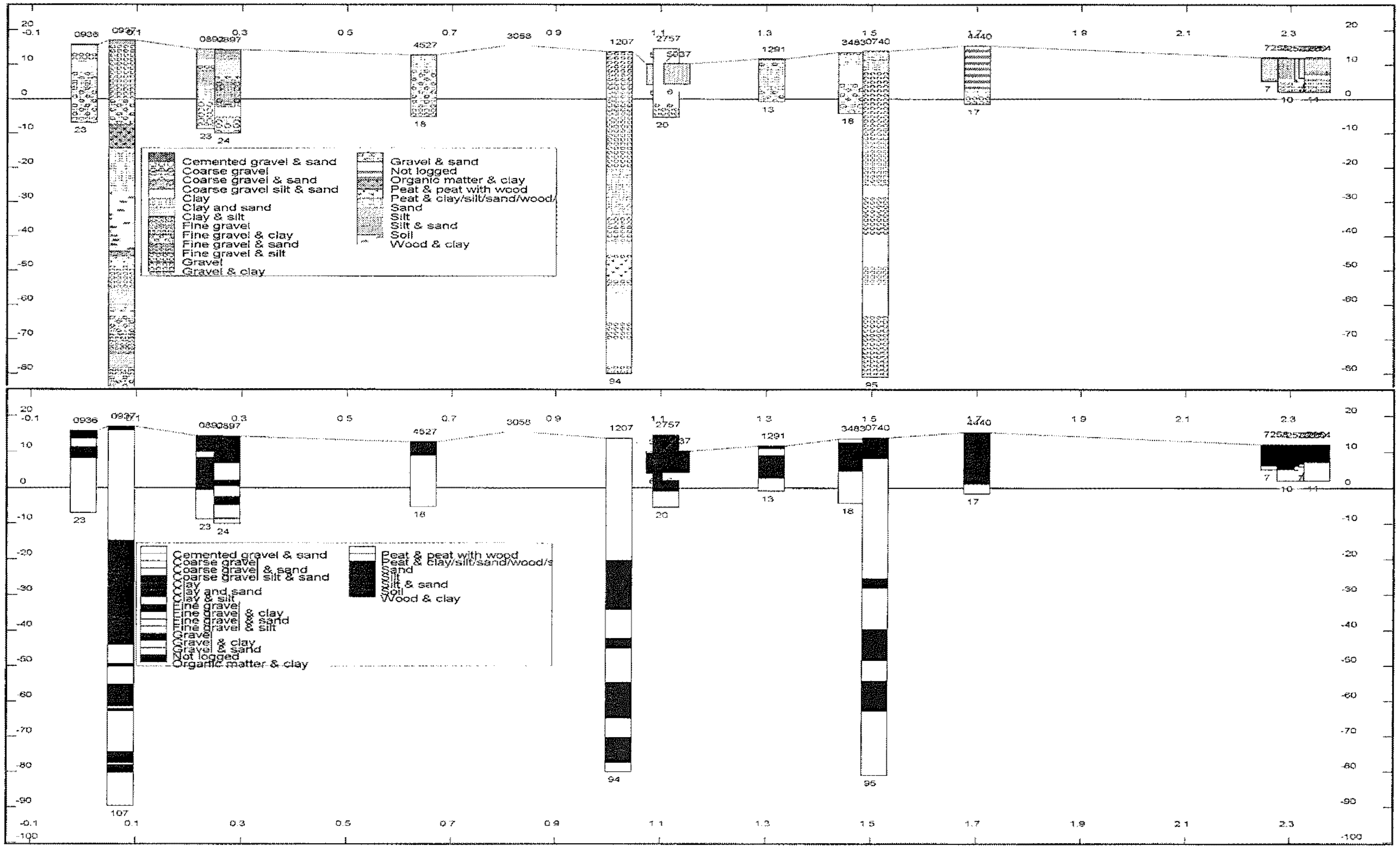


Figure 4-16 Halswell cross-sections, the lower showing simplified aquifers (white)/aquitard (black) classification

4.3.4 On Site Springs

All the springs at the site issue from mud/silt. No gravels or any material larger than fine sand were observed anywhere around the springs or in the streambeds.

The active springs on or around the Halswell test site include: M36/7314, M236/5620, M36/5877, M36/7231, M36/5934 and the spring mainly focused upon M36/5859 (Appendix F).

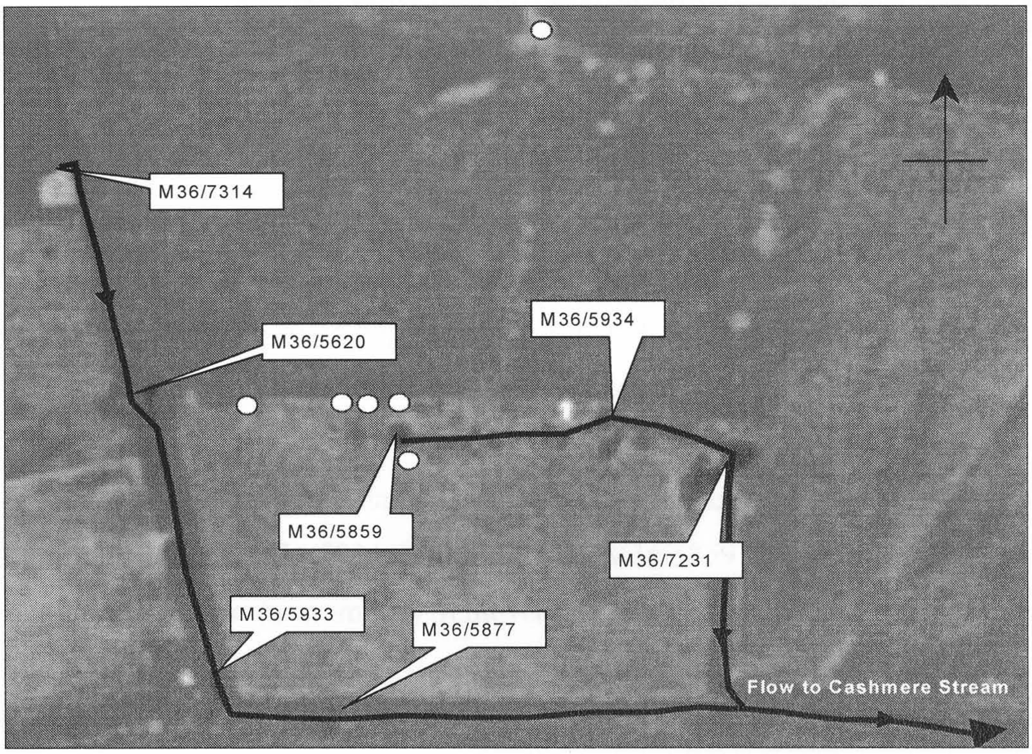


Figure 4-17 Halswell spring locations (white circles represent wells)

Artesian springs in Halswell are very different in appearance when compared to those of Brookside. The springs on site are generally made up of one large vent cone, and issue some meters away from one another. On average the vent fissures at the bottom of the cones are approximately 100 mm in diameter, with the vent cone extending out and up to produce structures often in excess of 1 m across.

The layout of springs, as can be seen from Figure 4-17, appears to be unnatural with very straight reaches and 90-degree changes in stream direction. The presence of a poplar windbreak is a likely cause for the formation of this angular occurrence of spring vents. The deep rooting (up to 4.5 m) poplar trees may have penetrated deep enough into the confining sediments to induce upward groundwater seepage, explaining why the spring system has formed following the path of the windbreak.

M36/7314 has a relatively deep pool, probably engineered as it supplies a small surface pump and was flowing at 4-5 l/s at time of testing. M36/5620 is a large vent structure in a deep pool which is rumoured to have discharged over 100 l/s, however was gauged at 21 l/s. M36/5933 is a smaller vent structure than M36/5620, being approximately 1 m in diameter, occurring in the middle of the streambed, and issuing water at an average rate of 20 l/s. M36/5877 is an obscured vent, choked with weed, which occurs deep into the stream bank next to some poplar trees that may have provided the mechanism for artesian vent formation. Flow was gauged at 25 l/s. M36/7231 is the largest pool on site. Gas effervesces freely from the vent, which discharged at 37 - 40 l/s. M36/5934 is another vent possibly induced by vegetation. This spring along with M36/5934, M36/7231 and M36/5859 closely follow the old poplar windbreak (now mostly removed). This vent pool and surrounding stream is covered with weed; flow is very hard to measure but was estimated at 20-30 l/s. M36/5859 has a large pool area but is not excessively deep except close to the spring vent. This vent occurs at the head of the stream and vent flow has been measured between 12 and 17 l/s.

Total flow supplied to Cashmere Stream base flow by this relatively small area is in the order of 140-160 l/s. Gauging data can be found in Appendix G.

4.3.5 Site Set-up

Installation of new temporary observation and production wells was proposed due to a lack if existing wells. This was carried out with a small, trailer mounted, pile driving type drill rig, which drove 65 mm diameter wells via a single action gravity hammer. This installation method is not suitable for geological logging, however due to the wet ground conditions present at the site initial attempts using cable tool techniques were abandoned, and the lighter driving rig was employed to sink five wells in close proximity to the target spring, M36/5859 (Figure 4-18 and Table 4-6). The well installation involved the driving of pointed pipes into the ground to depths between 6 and 12 m, with well screens consisting of drilled casing. 2.5 m screens were installed on two possible production wells M36/7253 and M36/7254 and 1 m screens on all other observation wells. Casings were easily driven through the confining material and into an aquifer of free running fine gravel. This method of piezometer installation proved quick, convenient and economical.

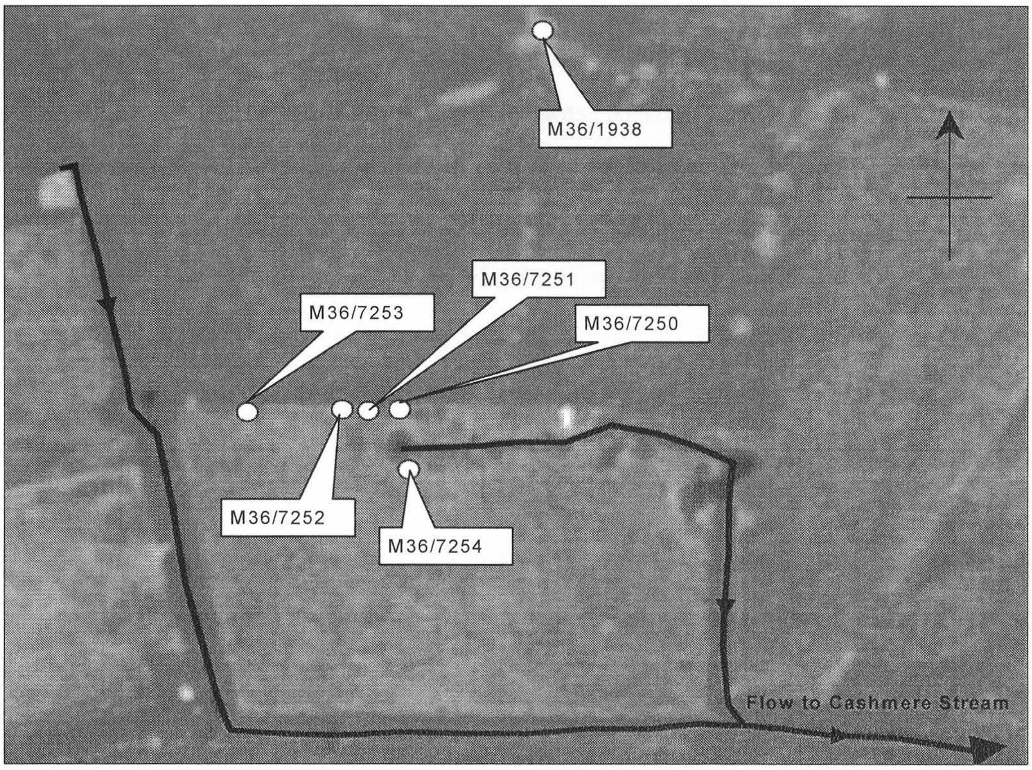


Figure 4-18 Halswell well layout

Well	Depth(m)	Rel Height	mEasting	mNorthing
M36/1938	12	-0.340	2476499	5735940
M36/7250	6	0.000	2476455	5735808
M36/7251	7	0.312	2476446	5735808
M36/7252	10	0.210	2476437	5735809
M36/7253	7	0.380	2476405	5735808
M36/7254	10	0.215	2476456	5735781

Table 4-6 Halswell well data

4.3.6 Testing

4.3.6.1 Test Procedure

A series of pumping tests were carried out on wells M36/7253 and M36/7254. The low performance of the temporary production wells reduced the pressure ranges that could be induced. It was originally hoped that the output from the pumped wells would match or exceed flow from spring M36/5859 (12 to 17 l/s), however obtainable discharge was lower than this. The reduced performance of the temporary wells is likely to be due to the small well-rounded gravels of the aquifer sealing the drilled screens of the wells. This limitation required a second method of testing to be employed. The outflow stream level from spring M36/7254 was raised to increase the spring back-pressure, and consequently reduce the pressure differential across the artesian vent.

Testing at Halswell was also carried out in three stages: the first involved pumping from well M36/7252, discharging the water into the drain to the west of spring M36/7254 and monitoring groundwater levels in all other wells; the second was pumping from well M36/7254 and discharging to the stream downstream of the weir and monitoring groundwater levels in all other wells; and finally the alteration of the stream level.

4.3.6.2 Test Set-up

Spring M36/5859 issues from a large vent in the middle of a paddock. The discharge pool then flows into a small ditch toward M36/5934 and out into Cashmere Stream. The confined discharge of the spring area provided an ideal point at which to measure spring/ stream flow discharge.

A V-notch weir was installed 15 m downstream of the spring vent. Again the weir consisted of a 2 mm stainless steel faceplate mounted on a plywood backing to provide a sharp crested weir. This was complemented by a 5 m 'Diver' and later by a 'hydrologger' water level recorder. The weir was levelled to within 1mm and the resolution of the water level recorder was 1 mm.

Water was discharged either downstream of the weir (stage two) or to the west into the neighbouring tributary (stage one).

'Divers' were employed in all observation wells two days prior to the testing period. These automatic transducer/recorders were supplemented with manual well readings. An acoustic Doppler flow meter was employed on the pumping well at various times to measure the flow rate from the abstracting wells.

4.3.6.3 Stage One - M36/7252

Water was abstracted from well M36/7252 and discharged into the ditch to the north near spring M36/5620. The well was pumped at varying rates from 2 to 8 l/s (15-50% of spring M36/5859 discharge)(Table 4-7), and measurements were taken in all other observation wells.

Date	ON	Rate (l/s)	OFF	Rate (l/s)	Notes
15-Nov	11:20	5	19:00	4.9	
18-Nov	10:15	6.2	14:30	6.3	
18-Nov	15:30	2.5	18:30	3.3	
20-Nov	10:40	7.5	16:00	7.4	Pulsing

Table 4-7 Halswell, well M36/7252 test data

4.3.6.4 Stage Two - M36/7254

Water was abstracted from well M36/7254 and discharged into the stream downstream of the weir near spring M36/5934. Again lower pumping rates than were planned were obtained, due to poor performance of the pumped well (Table 4-8). Figure 4-19 shows the measured aquifer response and changes in flow from spring M36/5859 due to pumping.

Date	ON	Rate (l/s)	OFF	Rate (l/s)	Notes
21-nov	11:55	3.1	15:16	3.0	
21-Nov	15:16	4.2	17:05	4.1	
22-Nov	12:13	5.5	16:25	5.0	
25-Nov		5			10 min

Table 4-8 Halswell, well M36/7254 test data

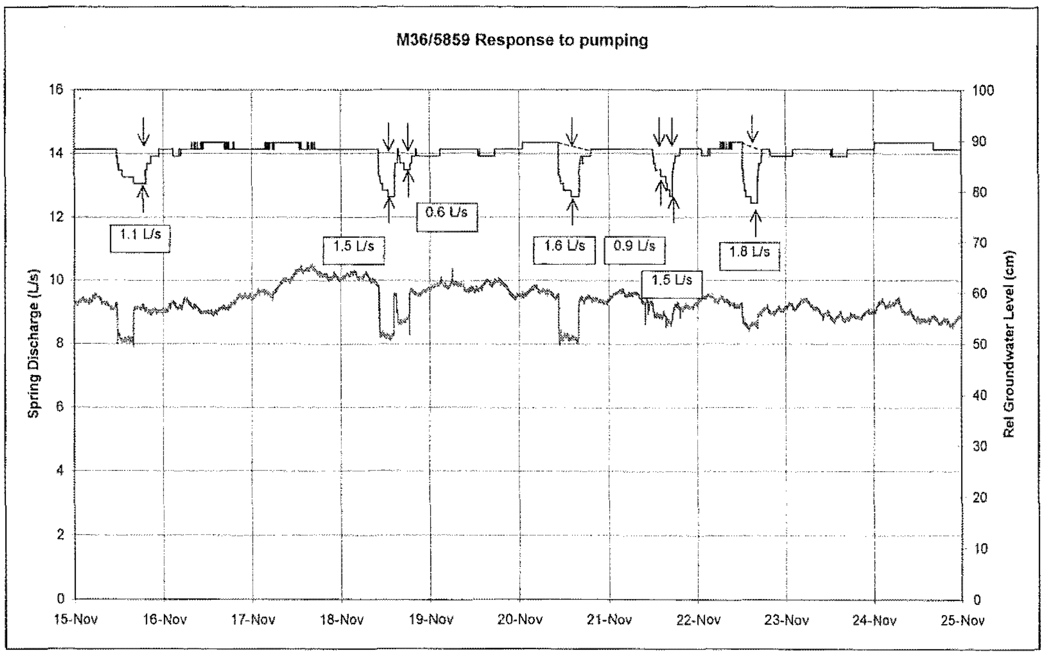


Figure 4-19Aquifer and spring responses due to pumping at Halswell.

Observed aquifer responses can be found in Appendix L, and raw test data in Appendix N (CD).

4.3.6.5 Stage Three - Stream Level Variation

Initially designed to provide a check of aquifer pumping, this test became a very useful method of varying spring discharge. Instead of aquifer pressure being reduced below the spring by pumping, increasing the exit level of water from the spring was used to reduce the hydraulic pressure differential. This was achieved by installing a plywood dam between the spring and weir. A 'diver' in the spring itself monitored spring water level and 'hydrologger' monitored weir discharge. The dam level was varied causing the water level above the spring vent to change.

Two periods of testing were carried out using the above method, the first period of two days from 25 to 27 November 2002. From the data obtained, the spring discharge appears to stabilise in as little as 20 minutes after over-topping of the temporary dam (Figure 4-20). The second test was carried out during the following week only taking one day with an hour allowed for stabilisation after over-topping of the temporary dam (Figure 4-21). See Appendix N (CD) for acquired test data. The use of a varied stream level to obtain changes in flow proved successful with very good repeatability of the experiment.

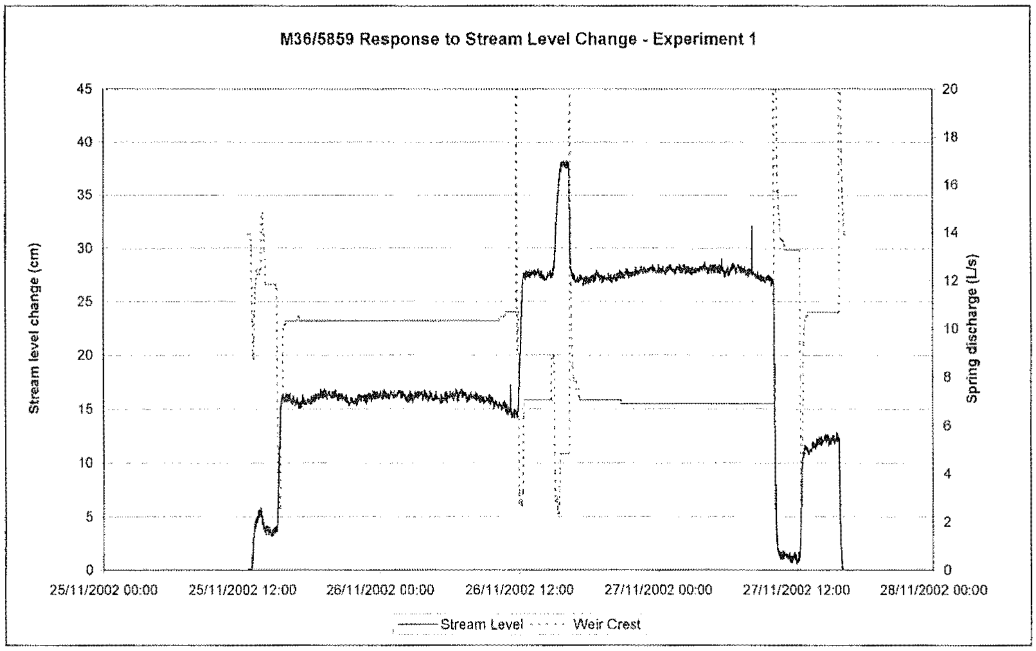


Figure 4-20 M36/5859 response to stream level change, experiment 1

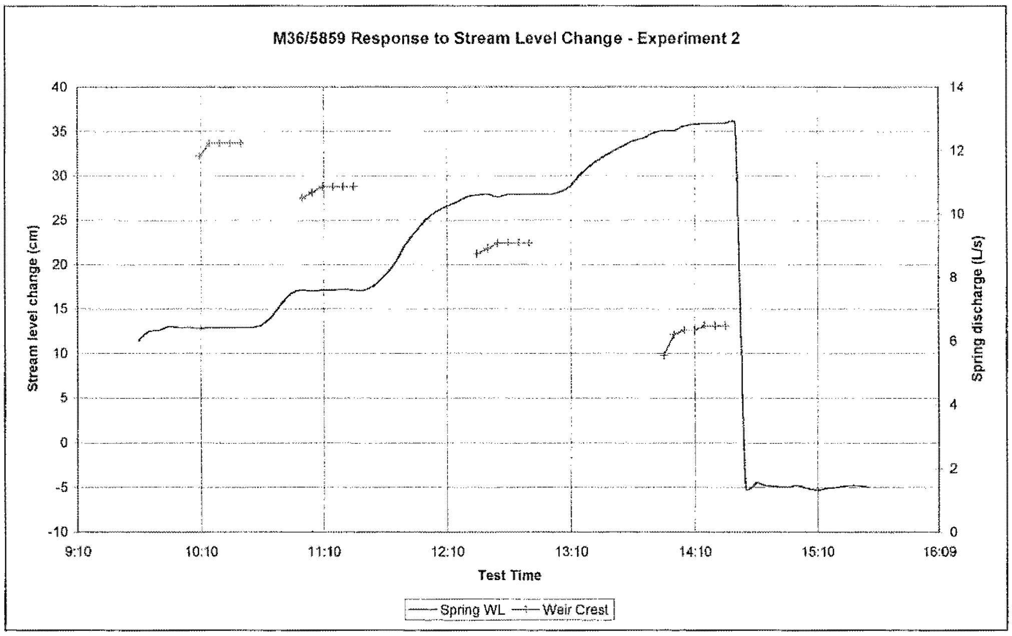


Figure 4-21 M36/5859 response to stream level change, experiment 2

4.3.7 Barometric Efficiency

Large atmospheric pressure changes (the equivalent of up to 50cm of water pressure) occurred during aquifer testing, however plots of groundwater levels vs atmospheric pressure do not indicate any significant relationship (Appendix K). It is therefore concluded that the Halswell test aquifer also has a low barometric efficiency and that the effects of air pressure change have a negligible influence on groundwater levels.

4.3.8 Aquifer Parameters

Aquifer test analysis of the wells on site indicates that the Hantush-Jacob (1955) leaky aquifer model best simulates the observed drawdown data. These observed data have not taken the change in flow from the spring into account, and as a consequence observed drawdowns may be less than what would have been observed with no spring present. The aquifer parameters are shown in Table 4-9, and analysis given in Appendix M.

Analysis	T (m^2/day)	S	β (m)
Theis	6000	.0003	N/A
Hantush-Jacob	3500	.003	228

Table 4-9 Halswell aquifer parameters

4.4 Chapter Synthesis

Testing was successfully carried out at both test sites, resulting in piezometric data, aquifer response data, and spring flow data. The data obtained from the test sites, when analysed, shows that a rapid, near immediate response in spring flow occurs as a pumping well's influence intersects a spring area. Any delays in observed spring flow response is due to storage of the streams between the target spring vent and the flow recorders and weirs.

Pressure changes at the springs were successfully induced by groundwater abstraction from the shallow aquifer, and piezometric drawdown toward the studied artesian spring systems was observed. This gives a strong indication that the upper aquifers serve as the primary source of water in these artesian spring systems.

The proposed methods of investigation proved successful, however the most effective method, being stream level change, was used out of necessity rather than choice. Poor performance of the temporary production wells, likely to have been caused by clogging of the slotted and drilled casings in the fine aquifer gravels, restricted the range of flows and therefore range of pressures that could be induced across the spring systems.

5 Analysis and Implications

5.1 Introduction

This chapter presents the analysis of data obtained from the two test sites, and tests the hypotheses outlined in Chapter 1. The first hypothesis, that the shallow aquifer is the source of water for the artesian spring systems, is tested by comparing theoretical piezometric contours to those observed in the field. The second hypothesis, that the aquifer pressure – spring discharge relationship is non-linear, is tested by comparing theoretical pumping-induced pressure change (drawdown) at the spring with measured spring discharge. Flow regimes and energy losses are examined to explain differences between expected and observed results. The implications of these results, in terms of water management, are then discussed.

5.2 Piezometric Analysis

5.2.1 Analytical Techniques

Testing of the hypothesis, that the upper aquifers are the primary source of groundwater flowing to the spring systems, involved analysis of the piezometric pressures surrounding the springs in the study areas.

The piezometric patterns for the two test sites were modelled using the groundwater model that most closely matched the nature of observed aquifer responses during pumping, in both cases the Hantush-Jacob model, and the aquifer parameters obtained (outlined in sections 4.2 and 4.3). Figures 5-1 and 5-4 represent the theoretical deformation of a horizontal, flat, piezometric surface due to groundwater flow toward the artesian spring systems. These patterns were generated using algorithms supplied by Bruce Hunt of the University of Canterbury that approximate the infinite series calculations used in the groundwater model, allowing for rapid calculation of predicted aquifer response to water abstraction and recharge. The models were then compared to observed water levels at the spring sites.

5.2.2 Brookside Piezometrics

Figure 5-1 gives the piezometric pattern generated for the Brookside site using the Hantush-Jacob groundwater model, assuming that the upper aquifer is the source of water (contour intervals are 0.02m).

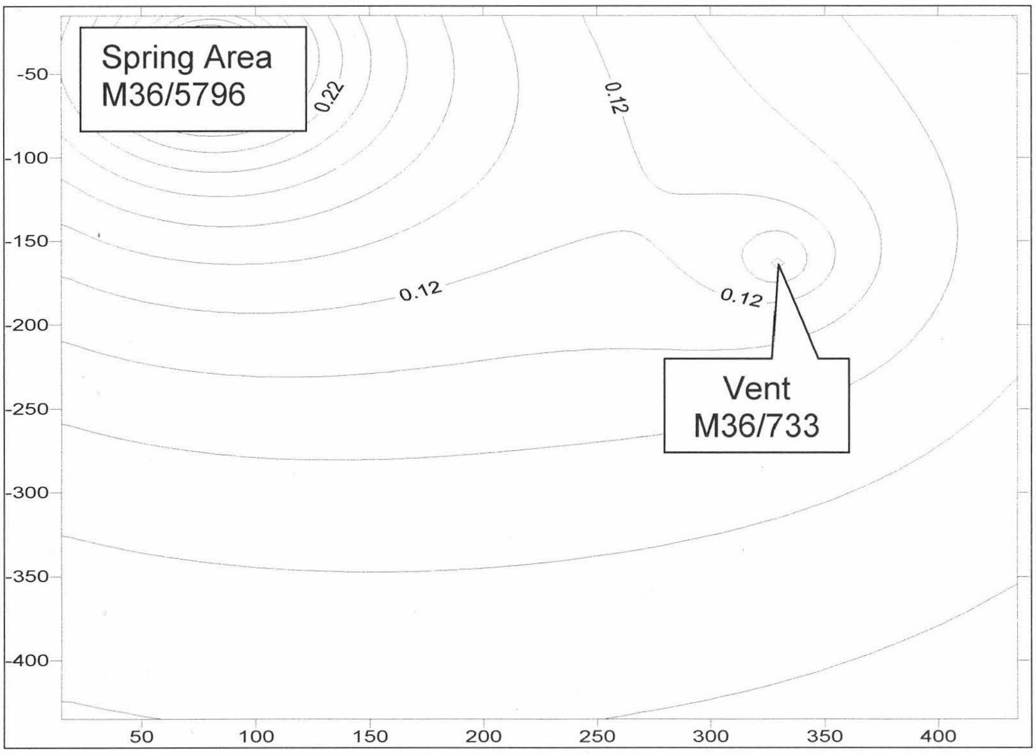


Figure 5-1 Modelled Brookside piezometric pattern

The model formed a piezometric surface comparable to the water levels observed in piezometers on site during the study prior to pumping. Figures 5-2 and 5-3 show the actual piezometric drawdown generated by groundwater flow toward the spring area M36/5796. The best-fit lines represent the Thiem (steady-state) groundwater model showing that the drawdown pattern is consistent with the steady state model until close to the spring. This indicates that the primary source of groundwater to the spring system is the aquifer located directly below the confining layer containing the spring fissure.

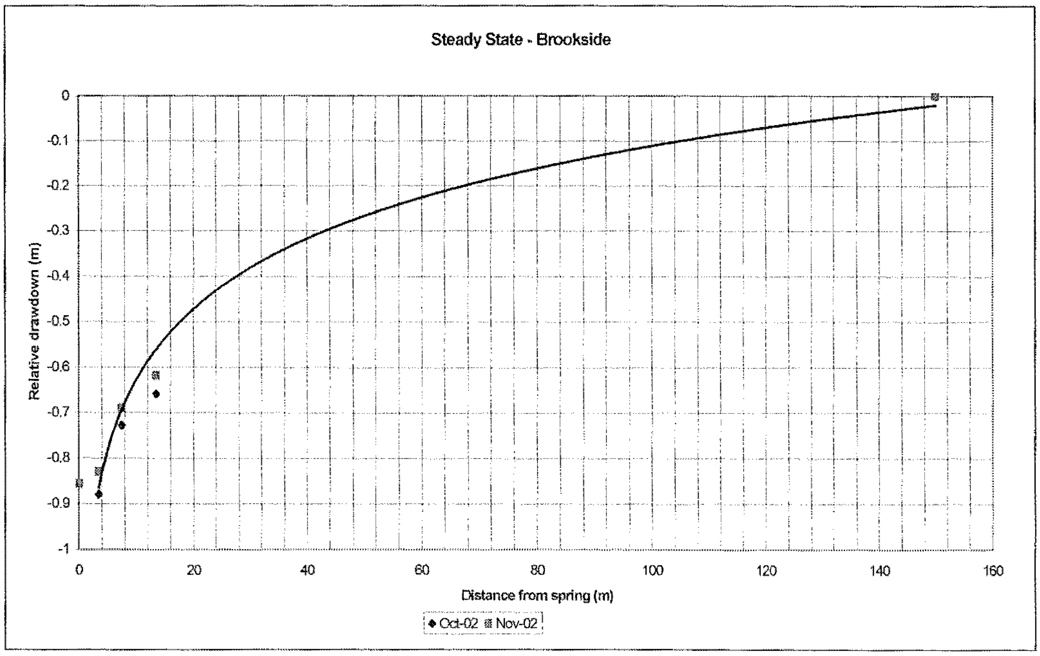


Figure 5-2 Spring induced piezometric drawdown at Brookside

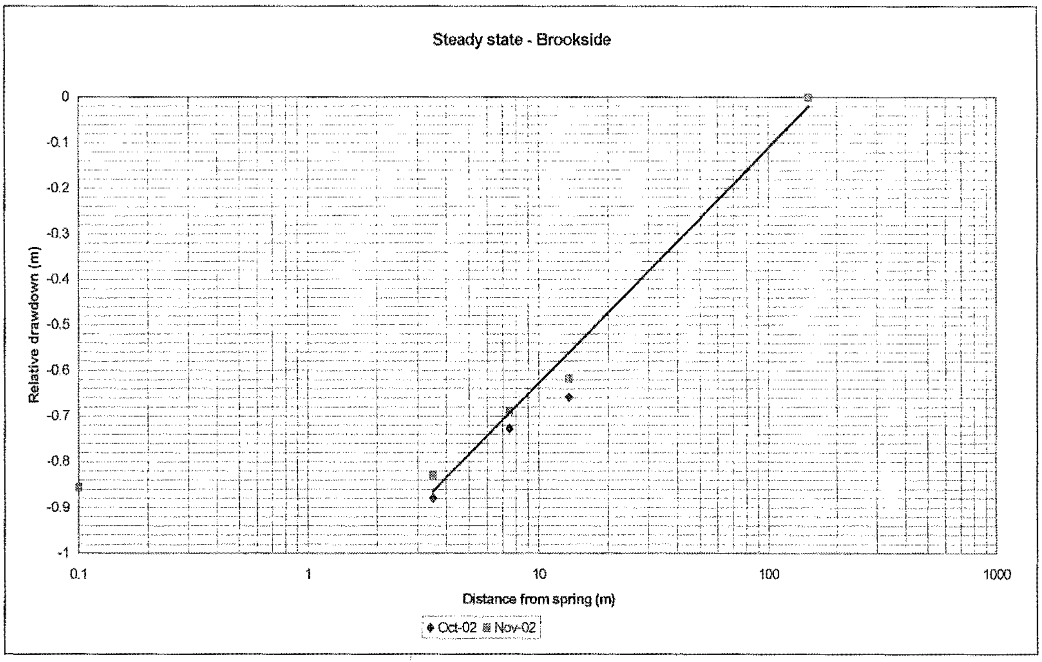


Figure 5-3 Semi-log plot of spring induced piezometric drawdown at Brookside

5.2.3 Halswell Piezometrics

Figure 5-4 gives the piezometric pattern generated for the Halswell site using the Hantush-Jacob groundwater model, assuming that the upper aquifer is the source of water (contour intervals are 0.05m).

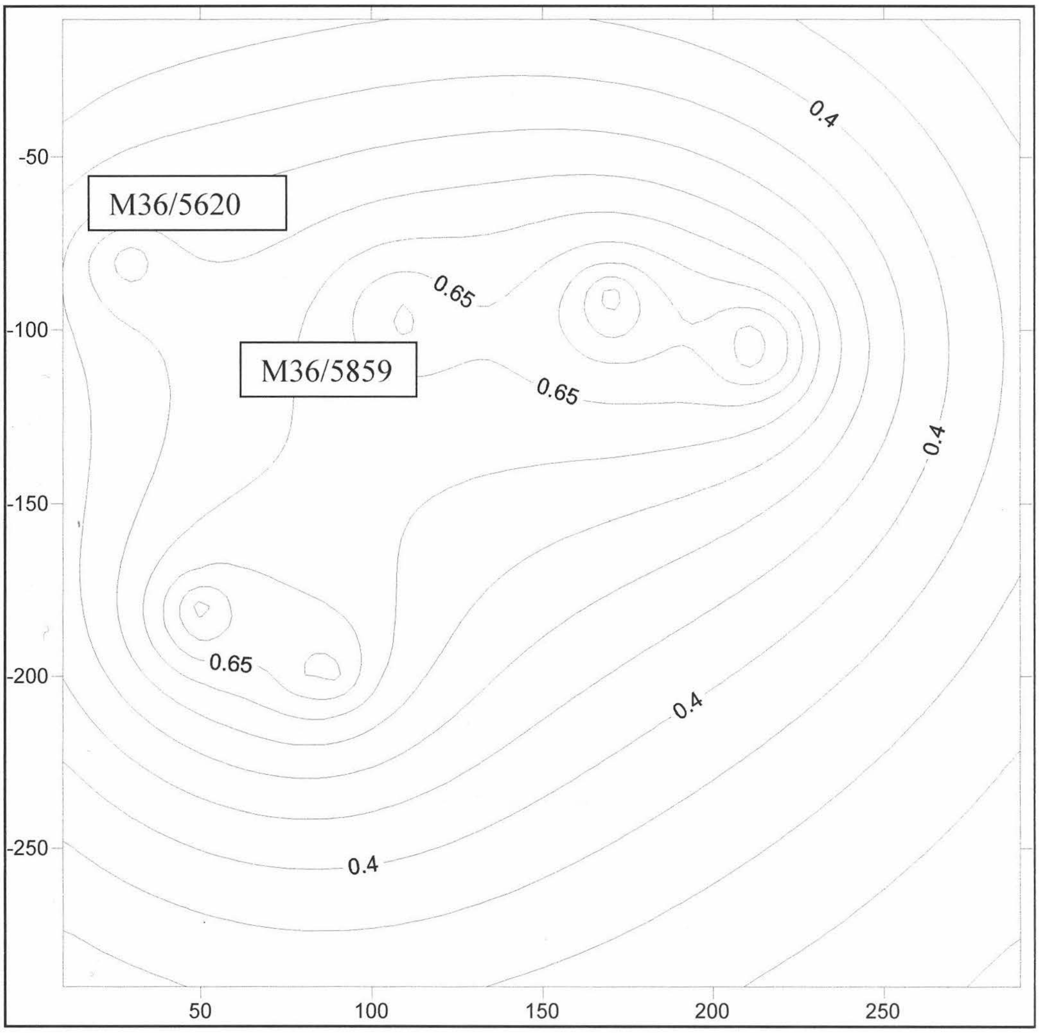


Figure 5-4 Modelled Halswell piezometric pattern

Again the model formed a piezometric surface comparable to the water levels observed in piezometers on site during the study, prior to pumping. Figures 5-5 and 5-6 show the actual piezometric drawdown generated by spring vent M36/5859. Again the drawdown pattern is consistent with the steady state Thiem model until close to the spring. The drawdown in this case, as indicated by the generated piezometric pattern plot, is the cumulative drawdown induced by each spring in the study area, creating a steeper best fit curve. The Thiem model analysis will consequently tend to underestimate the true transmissivity of the aquifer as the steeper the curve, the lower the transmissivity. Again the correlation of observed data and model prediction indicates that the primary source of groundwater to the spring system is the aquifer located directly below the confining layer containing the spring fissure.

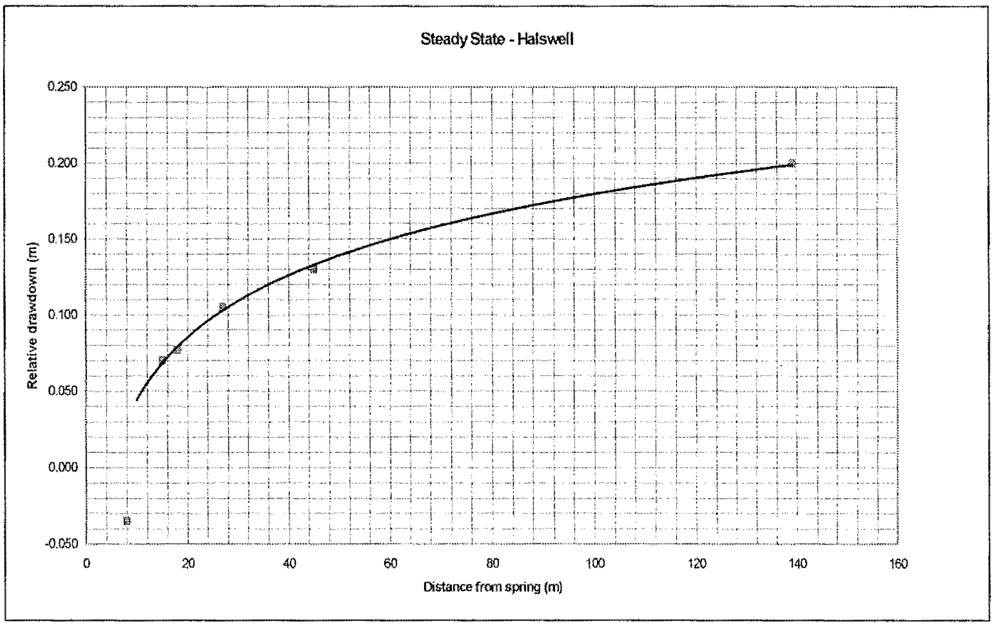


Figure 5-5 Spring induced piezometric drawdown at Halswell

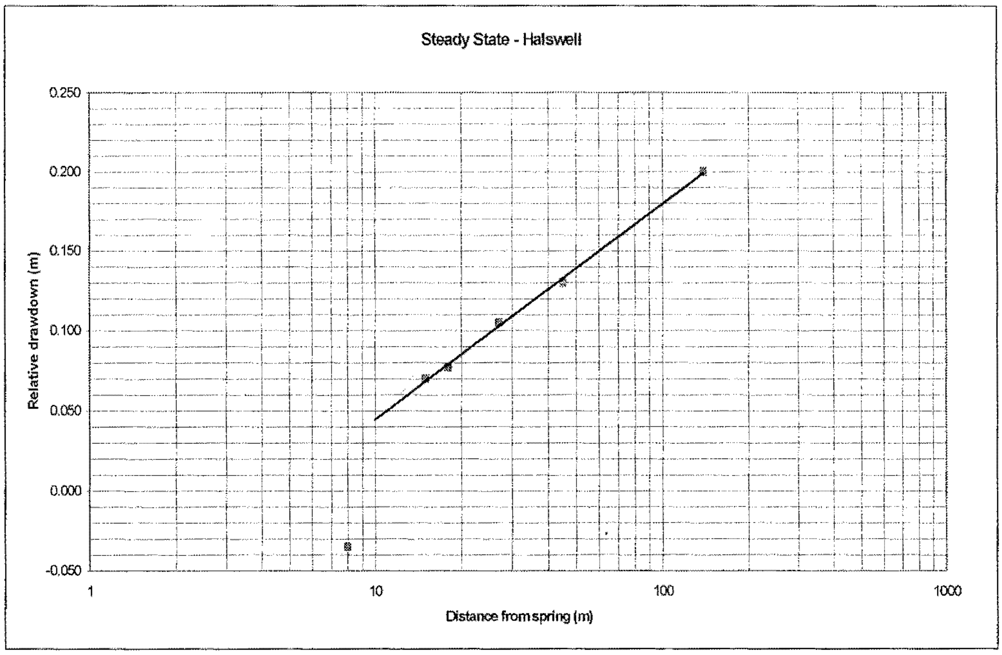


Figure 5-6 Semi-log plot of spring induced piezometric drawdown at Halswell

In both test cases the observed data is consistent with the hypothesis that the upper aquifers are the primary source of groundwater for the spring systems.

5.3 Artesian Pressure – Spring Discharge Relationship

With the primary source of groundwater feeding the test spring systems being confirmed as the aquifers immediately below the spring vents, analysis was carried out on the impacts of abstraction from the source aquifers.

5.3.1 Change in Observed Spring Flow due to Abstraction

Theoretical pressure changes induced at the spring vents during pumping were modelled for each test site using the Hantush-Jacob model, with aquifer parameters derived from testing (see sections 4.2 and 4.3) and observed water level drawdowns from the installed piezometers. The theoretical pressure changes (drawdowns)(Table 5-1) at the springs were then plotted against the measured spring discharges to determine the physical relationship between aquifer pressure and spring discharge (Figures 5-7, 5-8, 5-9 and 5-10). In all cases, the relationship is linear (first-order) which does not match the expected non-linear response. It thus becomes apparent that the relationship is simply a function of cross-sectional discharge area, spring pool elevation (back-pressure) and aquifer properties, which will be unique to each spring vent or swarm of vents, and is independent of the dynamics of groundwater flow.

	Calculated Hantush-Jacob (no storage in aquitard) Drawdown						
Q L/s	T m2/d	S	B m	R m	Time days	Draw Down m	u
4.9	3500	0.003	228	27	0.3	0.044	0.0005207
6.3	3500	0.003	228	27	0.18	0.056	0.0008679
3.3	3500	0.003	228	27	0.21	0.029	0.0007439
7.4	3500	0.003	228	27	0.22	0.066	0.0007101
3	3500	0.003	228	8	0.14	0.041	9.796E-05
4.1	3500	0.003	228	8	0.08	0.055	0.0001714
5	3500	0.003	228	8	0.17	0.068	8.067E-05
10.51	4800	0.02	457	175	1	0.032	0.031901
16.96	4800	0.02	457	175	0.83	0.050	0.038435
23.59	4800	0.02	457	175	1	0.072	0.031901
8.96	4800	0.02	457	175	1	0.027	0.031901
26.94	4800	0.02	457	175	0.95	0.082	0.03358
10.51	4800	0.02	457	310	1	0.018	0.1001042
16.96	4800	0.02	457	310	0.83	0.028	0.1206074
23.59	4800	0.02	457	310	1	0.041	0.1001042
8.96	4800	0.02	457	310	1	0.015	0.1001042
26.94	4800	0.02	457	310	0.95	0.046	0.1053728
	Calculated Theis Drawdown						
Q L/s	T m2/d	S	B m	R m	Time days	Draw Down m	u
11.2	13000	0.1	n/a	20	0.21	0.030	0.003663
4	13000	0.1	n/a	20	0.25	0.011	0.0030769
9	13000	0.1	n/a	20	0.21	0.024	0.003663
7.9	13000	0.1	n/a	20	0.18	0.020	0.0042735
5.5	13000	0.1	n/a	20	0.2	0.015	0.0038462
12	13000	0.1	n/a	20	0.27	0.034	0.002849

Table 5-1 Theoretical induced drawdowns due to pumping

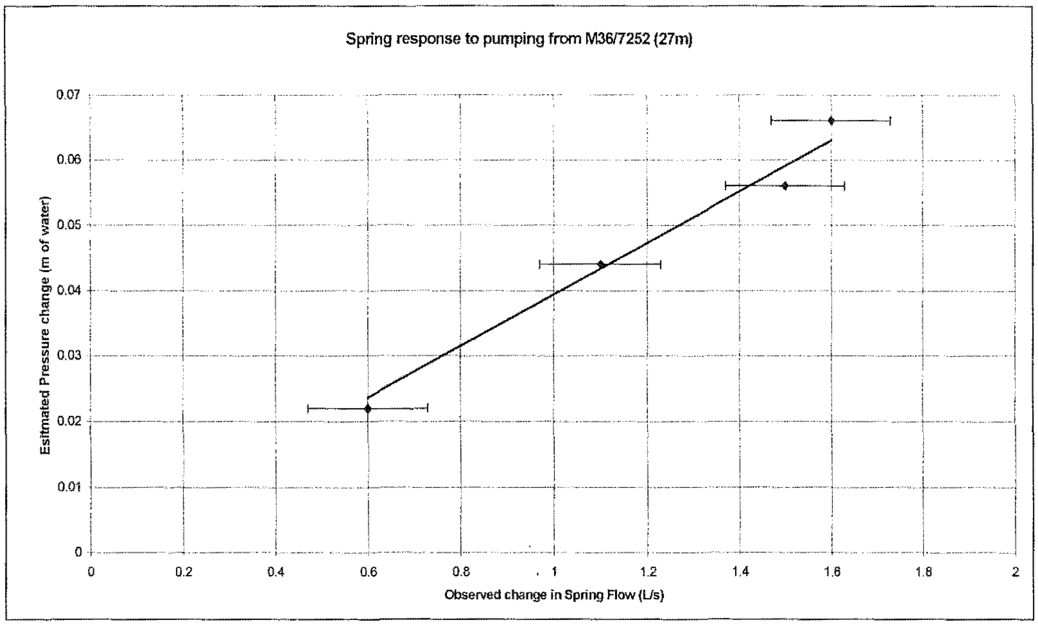


Figure 5-7 Aquifer pressure - spring flow curve Halswell #1

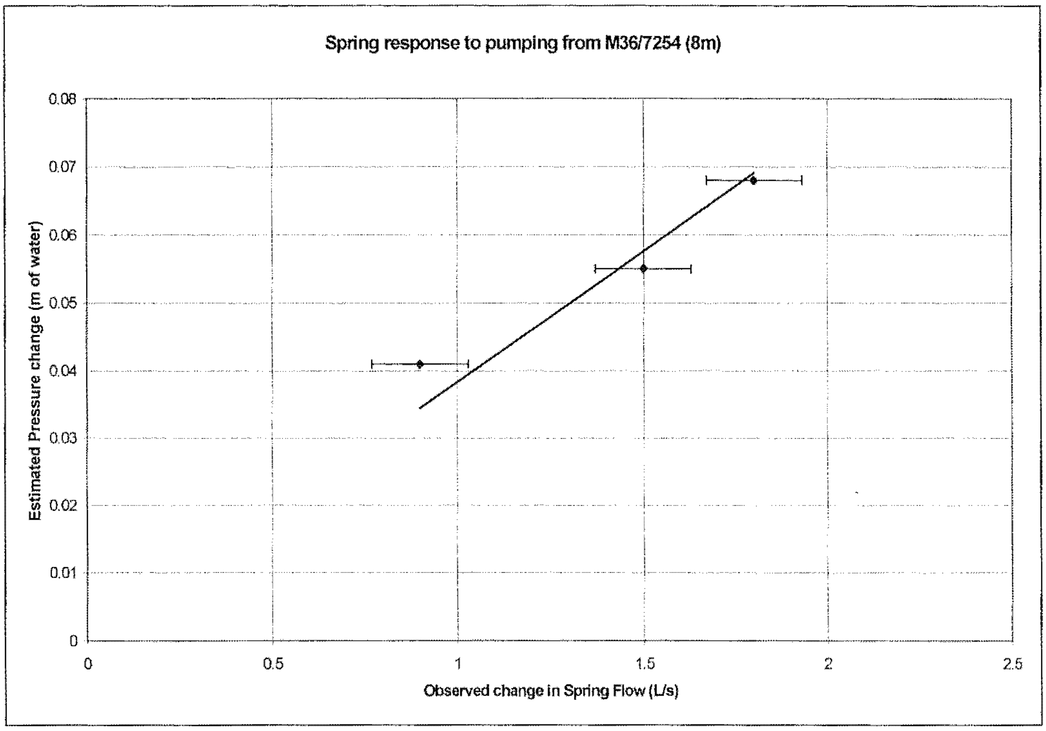


Figure 5-8 Aquifer pressure - spring flow curve Halswell #2

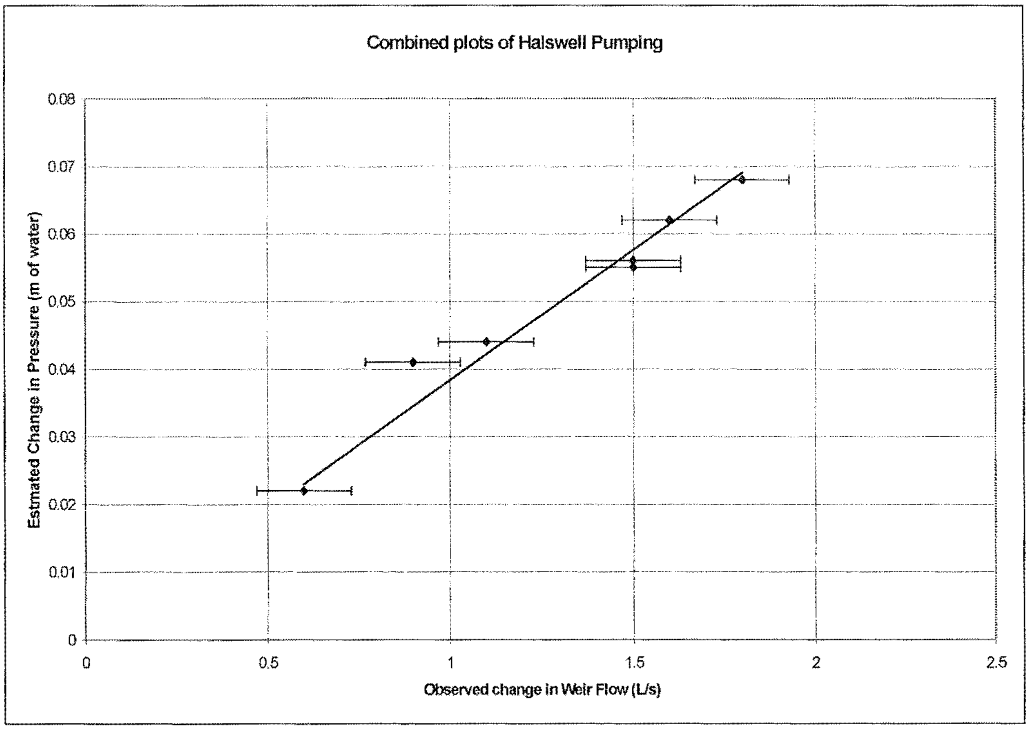


Figure 5-9 Combined plots of Halswell pumping data

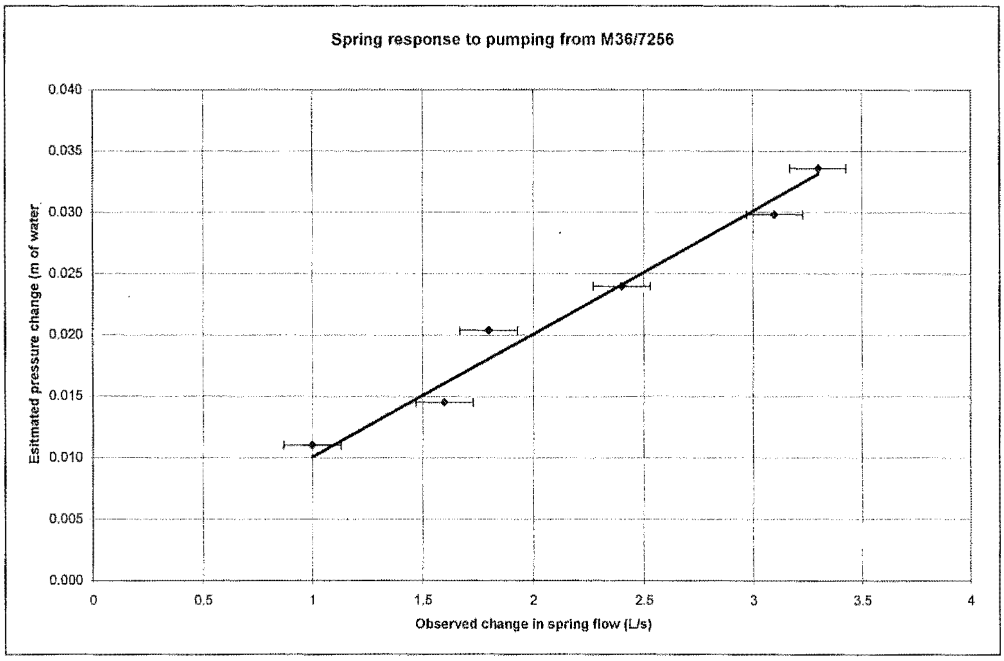


Figure 5-10 Aquifer pressure - spring flow curve Brookside M36/7256

5.3.2 Change in Spring Flow as a Function of Distance from Abstraction

As piezometric surface drawdown due to flow to a spring is proportional to the rate of groundwater flow to the spring, it follows that spring flow interference, due to changes in aquifer pressure, will vary with radial distance from the spring, as the cross-sectional area available for groundwater to move through dictates the change in aquifer pressure.

As pumping at Brookside simultaneously influenced two separate spring systems, it is possible to determine the amount of interference occurring at any radial distance from the pumping well. Plotting the ratio of drawdown vs pumping rate from the pressure-flow relationships determined in Figure 5-11, and assuming that pumping from directly below a spring will yield a 1 to 1 relationship of pump rate to spring flow reduction results in the plot shown in Figure 5-12. Negating any effects of stream level change this assumption of a 1 to 1 relationship will be valid, as the abstracting pump will intercept groundwater before it enters the streambed.

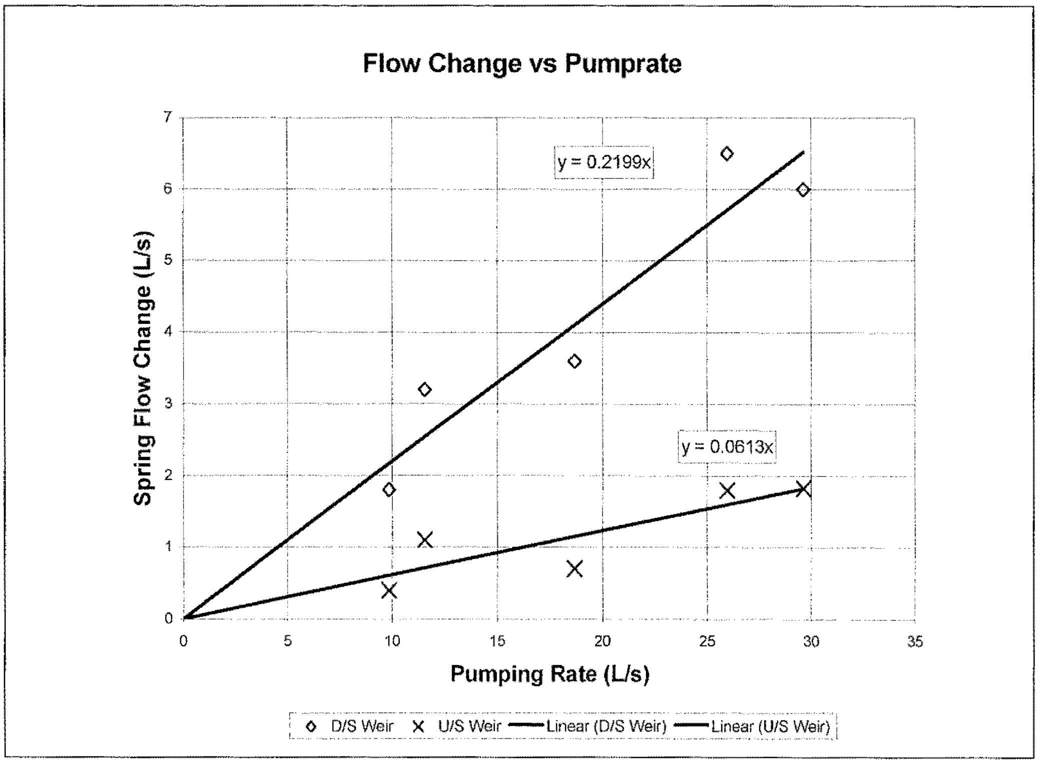


Figure 5-11 Flow depletion due to pumping at Brookside - simultaneous flow rates

The curve shown in Figure 5-12 is consistent with the groundwater model prediction for pumping induced drawdown, and it follows that the spring depletion factor will be directly proportional to pumping rate and duration. In the case of a non-linear relationship between aquifer pressure and spring flow this would not be true with the depletion factor being a function of drawdown, and spring vent characteristics.

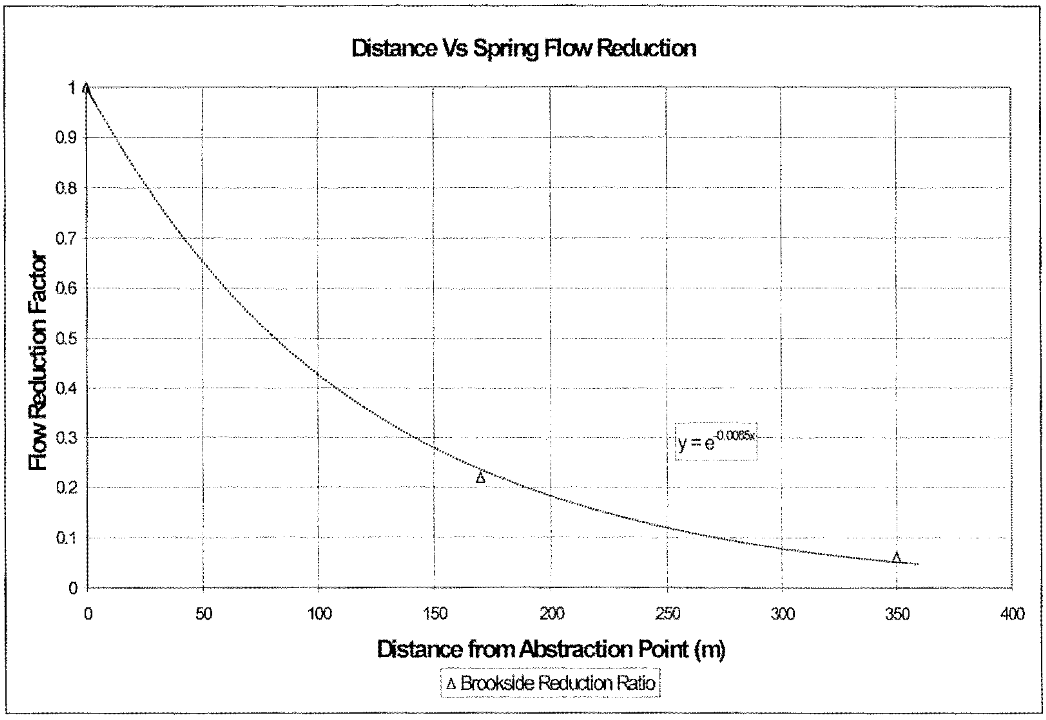


Figure 5-12 Flow reduction curve for M36/3548 at Brookside t = 1 day

The flow reduction factor is simply the percentage of the pumping rate that artesian spring discharge will be reduced by, unique to these springs.

Reduction factor = $e^{-(rk)}$ (5-1)

where:

- r is the radial distance (m) from the abstraction point
- k is a constant and is a function of aquifer parameters, T, S and pumping time for the specific site

5.3.3 Change in Observed Spring Flow with Back-Pressure

As an alternative to abstraction, where aquifer pressure is changed upstream of a spring vent, a change in spring discharge should also be observed by increasing the elevation of the spring pool and thus increasing the back pressure acting on the spring vent. This was achieved by damming the stream downstream of the springs, as outlined in sections 4.2 and 4.3 and measuring the spring pool level, or stream depth, and spring discharge. Plotting the stream depth against spring discharge for data obtained at the Halswell site during two separate experiments yields Figures 5-13, 5-14 and 5-15.

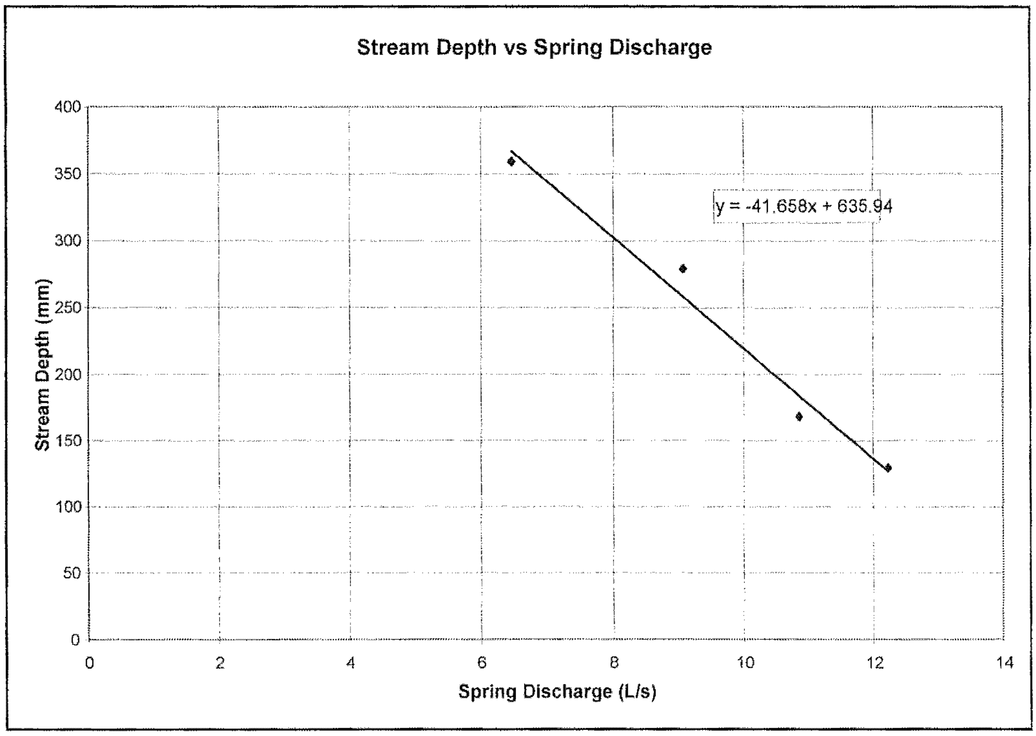


Figure 5-13 Stream depth test #1

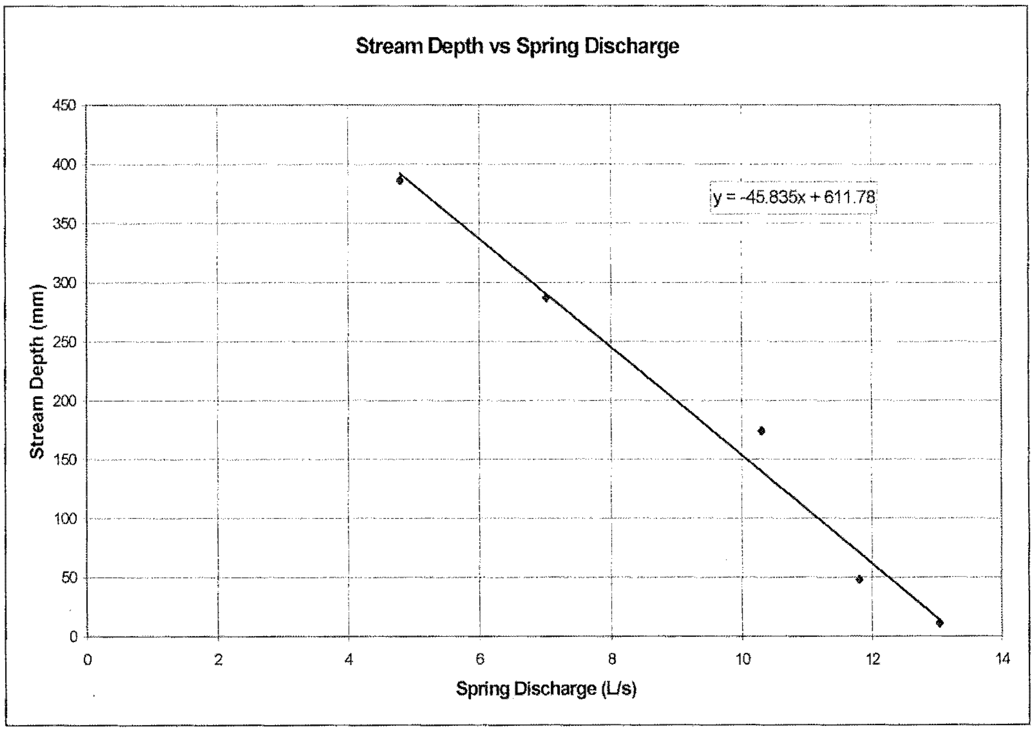


Figure 5-14 Stream depth test #2

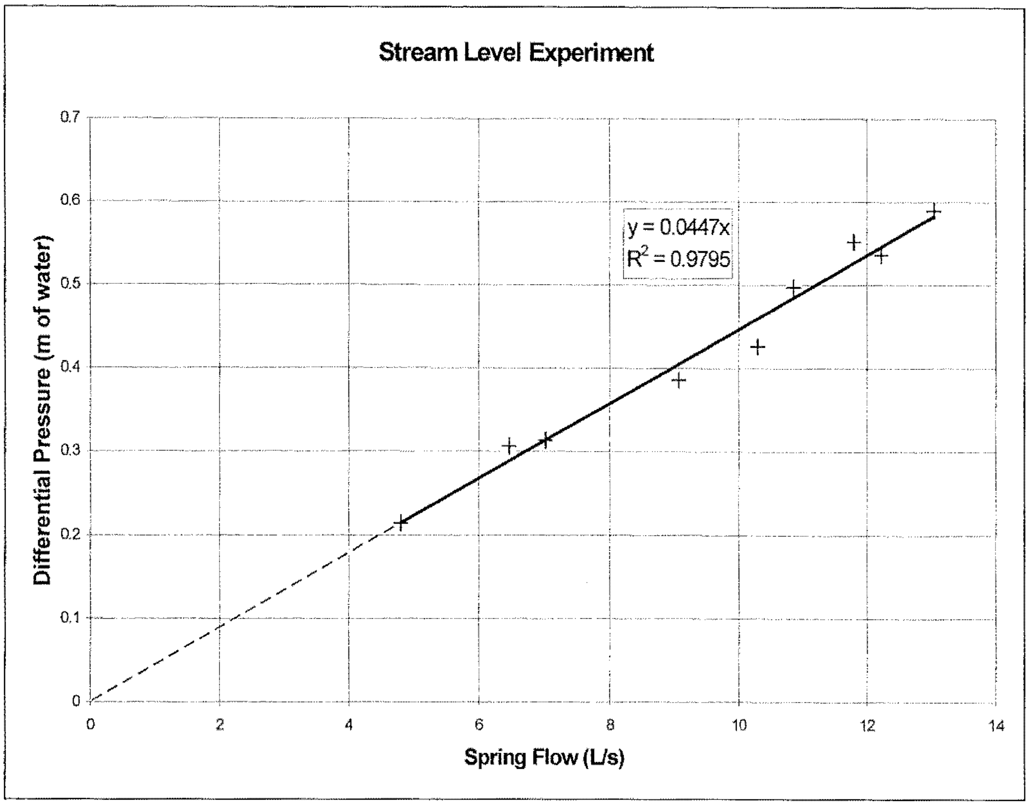


Figure 5-15 Combined plots of stream level experiment

Once again the pressure-discharge relationship in both cases was observed to be linear, or first-order, again not matching the expected non-linear response. The combined plot (Figure 5-9) shows good data correlation and repeatability of the experiment.

The data acquired during these stream level experiments provide one of the largest ranges of spring flow obtained during this study. Discharge from spring M36/5859 ranged from 13.5 l/s to 4.8 l/s which equates to around 65% of the total possible flow range. This range included the maximum water velocities where most discharge variation due to a non-linear relationship were expected.

5.3.4 Summary of Artesian Pressure - Spring Discharge Analysis

The observed relationship between aquifer pressure and artisan spring discharge is entirely first-order. This is not consistent with the hypothesis of a non-linear relationship.

5.4 Discussion

5.4.1 Observed Responses

The test sites at Brookside and Halswell represent two different occurrences of artesian springs. The springs at Brookside operate on a relatively low pressure differential across a thin confining layer, whereas the Halswell springs are driven by much higher internal aquifer pressures forcing water up through more than six metres of confining material. The higher pressure differential across the confining layer at Halswell gives higher maximum water velocities within the springs and the thicker confining layer produces larger, single spring vents, compared to smaller vent swarms at Brookside.

Even though the two test sites are different in terms of physical characteristics, the responses to pumping were similar, and the analyses consistent. The data acquired are therefore likely to be a good representation of artesian spring flow occurrence in Canterbury and the analysis methods should be applicable to all artesian springs throughout the region.

5.4.2 Piezometric Analysis

Piezometric data, spring response to pumping, and aquifer parameters all provide positive evidence that the upper aquifer is the primary source of groundwater flowing through the studied artesian spring systems.

The observed piezometric drawdowns do not perfectly match model predictions, however they are of a similar nature; the main sources of discrepancy are the limitations and assumptions used in the models, outlined in section 3.4.

5.4.3 Aquifer Pressure – Spring Discharge Relationship

5.4.3.1 Flow Regimes – Laminar or Turbulent

As seen in Chapter 3, the Reynolds number indicates laminar or turbulent flow in a fluid. The linear nature of the aquifer pressure – spring discharge relationship could be explained by having an entirely laminar flow regime at the aquifer-spring interface and through the spring fissure. Groundwater flow theories, as outlined in Chapter 3, however, suggest that this is unlikely, Reynolds numbers for groundwater flow were therefore calculated to determine whether the dominant flow regime was laminar or turbulent.

Reynolds numbers were calculated for both the spring fissure and the aquifer-fissure interface at spring vent M36/5859 at Halswell prior to testing. The worst case aquifer interface configuration A, where groundwater must pass through a narrow entrance to the fissure (see section 2.3), was assumed. This site was chosen as the spring vent fissure was well-defined and therefore easily measured, and it had the highest velocities, where turbulent flow is most likely. Using equation 3-3 with the following values gives the results shown in Table 5-2.

ρ = 999.70 kg/m^3 (fluid mass density)

μ = 1.308 x 10^3 pa.s (kinematic viscosity)

v = 1.90 m/s for the spring fissure (v=discharge/area using 15 l/s over a 100mm diameter vent), and

= 6.3 m/s for the aquifer-fissure interface (v=discharge/area using 15l /s over a 100 mm diameter vent with a gravel porosity of 0.30)

l = 100mm for the spring fissure (characteristic length), and

= 5mm for the aquifer-fissure interface (Average 10 mm gravel)

Flow Phase	**Estimated Velocity**	**Characteristic length (mm)**	**Reynolds Number, R_e**
Fissure	1.9 m/s	100	166 520
Aquifer-fissure interface	6.2 m/s	5 (half grain size)	27 169

Table 5-2 Halswell spring system R_e estimates

At high Reynolds numbers Darcy's Law becomes invalid and flow is turbulent. Therefore the estimates for Reynolds numbers shown in Table 5-2 indicate that fully turbulent flow is occurring both at the aquifer-spring interface and through the spring fissure.

Changing the spring pool elevation and thus the back-pressure on the spring induced the largest change in spring discharge, and the largest range of measured flows – 13.5 l/s to around 4.8 l/s. Corresponding changes in Reynolds numbers were calculated from the test data, to determine any changes in flow regime during the experiment, and are shown in Table 5-3.

Flow Phase	**Q = 13.5 l/s**	**R_e**	**Q = 4.8 L./s**	**R_e**
Fissure	1.7 m/s	148 992	0.6 m/s	52 585
Aquifer-fissure interface	5.7 m/s	24 978	2.0 m/s	8 764

Table 5-3 Range of R_e for observed spring discharges in Halswell

The calculated Reynolds numbers show that turbulent flow occurred at all the measured spring discharge rates during the stream level experiment. The values also indicate that the potential for turbulent flow increases with water velocity, as expected.

As turbulent flow was shown to exist both in the spring fissure, and at the aquifer-spring interface, at the Halswell site, the linear relationship between aquifer pressure and spring discharge cannot be simply explained by the presence of laminar flow. Fluid energy loss concepts must therefore be examined to explain the linear relationship.

5.4.3.2 Energy Loss

The change in energy of a water particle moving from the aquifer through the spring vent is as follows. At rest in the source aquifer the kinetic energy of a water particle is initially zero. The kinetic energy will rise with velocity according to $\frac{1}{2}mv^2$ and will therefore reach a maximum at maximum velocity. For example, at 5.7 m/s a water particle's energy can be approximated at 16.2xm Joules. Reducing the spring discharge to 4.8 l/s, a reduction of 65%, the maximum energy a water particle can have is 2xm Joules or only 12% of the initial discharge energy.

The field testing undertaken therefore covered a wide range of fluid energy states and although spring flow was never reduced to theoretical laminar flow conditions, changes in flow were induced over a sufficient range for the relationship between flow and energy loss to be observed.

The greatest deviation from a laminar pressure-flow relationship will occur when the water particles are travelling at high velocities or, similarly, at the highest spring discharge rates, i.e. that at which testing was carried out. The lack of observed deviation from a first-order relationship at the highest rate of discharge in all cases therefore indicates that energy loss across a spring system is proportional to the velocity of the fluid, and laminar type flow losses dominate.

5.4.3.3 Energy Loss in the Spring Fissure

Expected losses due to flow through the spring vent fissure, should have been observed as a departure from laminar flow. Figure 5-16 shows the expected head loss velocity relationship for a pipe with the same dimensions, 6m long and 100 mm in diameter, similar to the Halswell spring M36/5859.

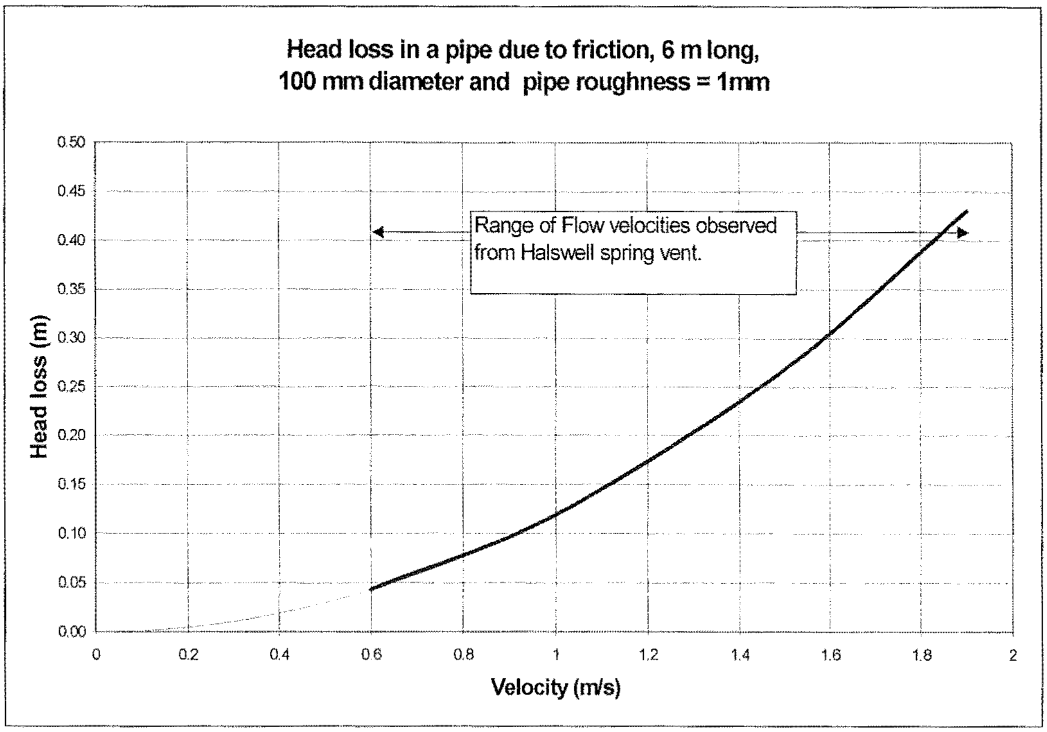


Figure 5-16 Theoretical head-loss in spring fissure

One possibility for the lack of observed deviation for the spring, is that the estimate of fissure size is incorrect. Sensitivity analysis of the Reynolds number, however, shows that flow will be turbulent for all reasonable estimates of fissure size (transition at 3.5 m diameter and laminar at 8 m), for the measured spring discharge rate of 15 l/s. An increase in vent diameter will, however, result in a rapid reduction in flow velocity and in turn the magnitude of pressure loss due to friction will also reduce significantly. Large vent openings of more than 100 mm were not present, thus the reason for a lack of departure from first-order loss must lie in the nature of the fissure itself, and its sub-surface dynamics.

Reasons for low energy loss in a spring fissure lie in the interaction of the water with the walls of the fissure. If the walls are very smooth then friction loss is reduced, but also if the boundary flow between the fissure wall and the majority of turbulent flow is large, the interaction of water with the fissure wall would also be reduced. A spring fissure is unlikely to be a straight structure and the dynamic shape resulting from spring formation could help to reduce the groundwater/fissure wall interaction. Near wall turbulent flow will result in increased erosion until equilibrium is reached, thus forming a feedback system during spring fissure construction. If equilibrium is not reached, then continual erosion of sediment should result in very large connecting structures between the aquifer and the surface streams. This is not observed, however, and it is concluded that flow regimes in the spring fissures are approaching equilibrium.

5.4.3.4 Energy Loss at the Aquifer-Spring Interface

From the analysis of the Halswell test site, turbulent flow in the aquifer matrix is likely to occur. Turbulent loss should begin when groundwater departs from Darcian (laminar) flow and transitions toward turbulent flow.

Analysis was carried out using the worst-case scenario with a small entrance to the spring fissure (configuration A from section 2.3). At some critical distance from the spring vent fissure the flow changes from laminar, where losses are proportional to velocity and therefore linear, to turbulent, where losses are proportional to velocity squared and therefore non-linear. For the first-order relationship obtained, the distance between this point and the spring fissure must be small enough that the impacts of turbulent losses as the water in the aquifer travels through this zone are not observed. In effect, turbulent flow, and a corresponding non-linear response does occur, but the area over which this occurs is so small that the effect is not measurable at the flow rates present in the springs tested. Reasons for this may lie in the configuration of the base of the fissure where it interfaces with the source aquifer. A larger flow area will allow entrance velocities to be minimised and decrease the influence of turbulent flow by maintaining more viscous interaction between water particles at the lower velocities. Alternatively, the conductivity of the aquifer just below the vent may be very high and any losses due to turbulent flow are negated by an overall increase in ease at which the groundwater is allowed to pass through. The combination of increasing conductivity and large fissure entrance is shown in Figure 5-17.

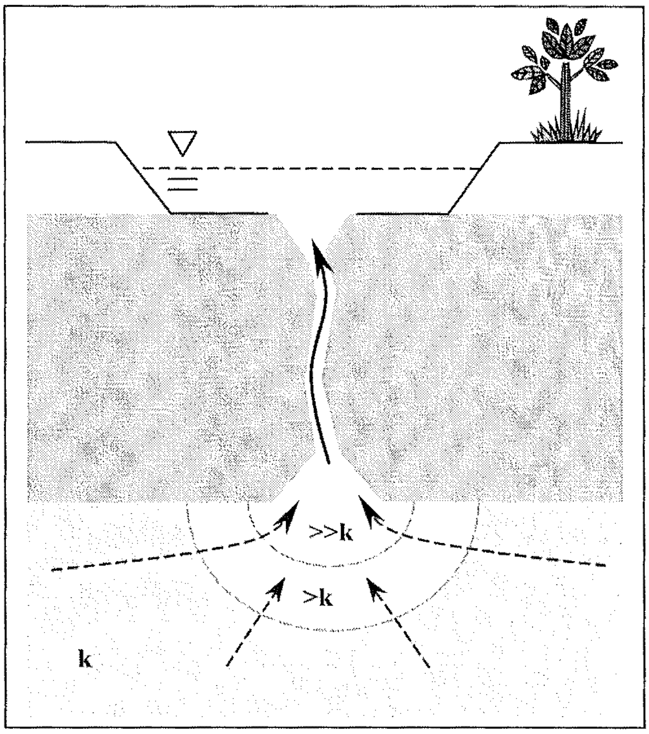


Figure 5-17 A low loss spring system configuration

The effects of localised increased conductivity of the aquifer will increase the effective radius of the spring. The resulting effect is that the radial distance from the spring centre, where flow is highest and therefore losses expected to be greatest, is increased and the associated energy losses reduced.

Random, turbulent flow in the aquifer matrix does not contribute significantly to pressure loss across an artesian spring vent.

5.4.3.5 Losses in Canterbury Spring Systems

If point source springs of higher discharge are encountered there may be cause for a greater, observable, departure from a first-order pressure-flow relationship. This is unlikely in Canterbury, however, as the maximum piezometric head in the upper aquifer is only 2 m above ground level. Areas of higher spring discharge are more likely to consist of spring vents with larger discharge areas rather than higher water velocities.

A first-order relationship between aquifer pressure and spring discharge simplifies the problem of predicting discharge by negating the effects of: pore size, effective porosity, fissure size and length, even the types of geology and permeabilities present. The change in flow of an artesian spring in Canterbury is only, and directly, related to the pressure differential across the spring fissure. This pressure differential is the change in pressure between the aquifer hydrostatic pressure (pre-development head) and the vent discharge pressure (spring pool head) (Figure 5-18).

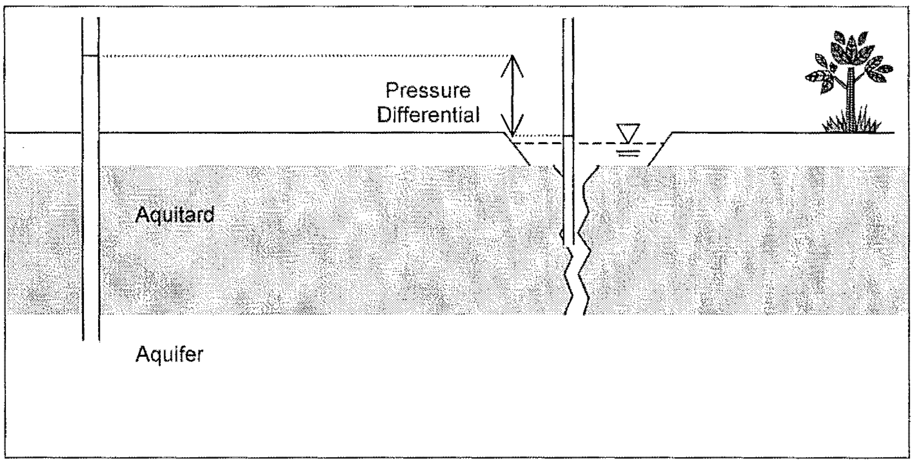


Figure 5-18 Pressure differential across a spring

5.4.4 Effect of Stream Level Change

It has been shown that increasing the elevation of the spring pool results in a reduction of spring discharge. Conversely reducing the level of water in the spring pool will result in an increase in the ease of water to flow from a spring vent. A reduction of flow from a spring will cause a reduction in the level of the stream draining the spring pool, and in turn reduce the pool elevation head. Although this will serve to buffer spring discharge rates, the relationship between changes in pressure differences and groundwater pressure are near linear. In the simplest case, where a stream has a square profile, the relationship is entirely linear shown in Table 5-4 and Figure 5-19 for a hypothetical spring driven by artesian pressures 1000mm above the streambed and drained by a stream 100 mm deep.

GWL (mm)	Pool/ Stream Level (mm)	Pressure Difference
1000	100	900
600	60	640
400	40	560
0	0	0

Table 5-4 Effects of pool level changes for a simple stream profile

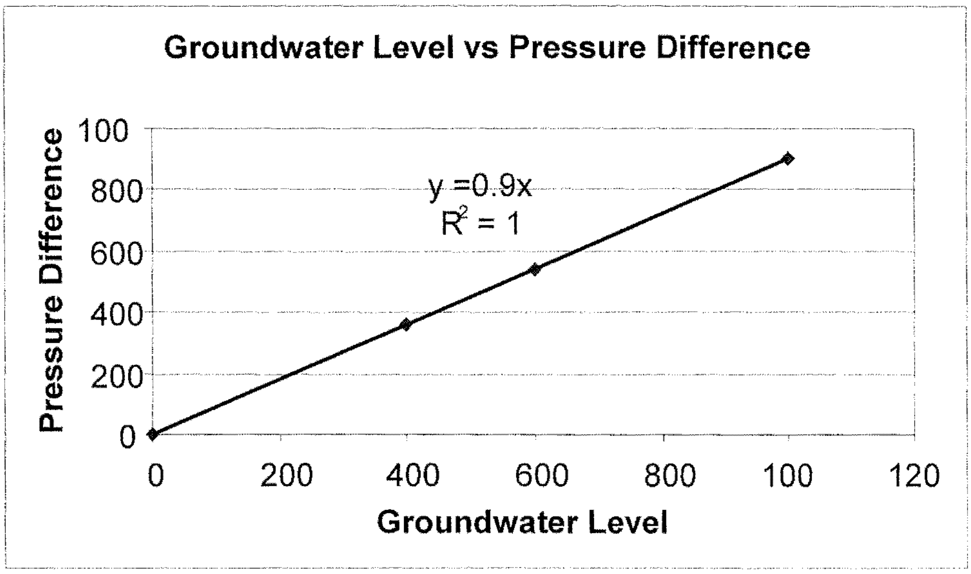


Figure 5-19 Plot of groundwater levels and pressure difference due to pool elevation

5.5 Implications for Management

The purpose of the analysis conducted in this study was primarily to observe the effects of localised pressure drops due to water abstraction close to an artesian vent. An expected non-linear relationship between aquifer pressure and spring flow would have provided a 'buffer' for spring discharge against abstraction induced pressure drops. The linear relationship obtained means that near spring abstractions have a much more direct effect. This relationship between pressure and discharge, however, is applicable to all pressure changes in the aquifer system, not just that of near spring interference from an abstracting well.

With the knowledge of how a system of springs will react to pressure changes in aquifer environment, predictions of the effects of proposed water abstraction can be made. Consequently if minimum spring flow rates are determined for environmentally sustainable conditions, the maximum amounts of water that can be abstracted from the upper aquifer systems can be readily determined.

Any water abstraction will have an effect on confined aquifer pressures. Confined aquifer pressures respond much more rapidly to water abstraction than that of unconfined aquifers. This is because much of a confined aquifer's pressure is derived from the loading of the water in the aquifer matrix from material above the upper confining layer. As a result, for a given amount of water removed a much larger change in pressure will occur in a confined aquifer when compared to the pressure response of an unconfined aquifer.

Near vent pumping will have a larger, more rapid, effect upon the performance of spring flow than overall aquifer pressure reduction, but conversely the rate at which a spring will recover at the termination of pumping is also very much higher. The responses to pumping and reductions in pumping in the source aquifer have immediate effects, and only the overall reduction in aquifer pressure will degrade spring performance in the long term.

The effect of near vent pumping is similar to well interference. Therefore interference, from local effects, can be estimated using the same well interference techniques.

5.5.1 Determining the Effect of Abstraction

Starting with the calculated aquifer parameters of the study area, and noting the groundwater model used to approximate observed aquifer response, the same model can be used to predict pressure change across a spring area. This should be done by using the projected water levels of the area without the effect of the spring drawdown.

Using either two points of flow and correlated groundwater levels, or using stream level as an approximation of water pressure downstream of a spring system, an aquifer pressure-spring discharge relationship curve for the target spring can be constructed.

The pressure change calculated from the groundwater model will be directly reflected in the spring flow rate. Halving the artesian pressure of the aquifer will result in halving spring flow, and can be read off the pressure-flow curve.

5.6 Chapter Synthesis

There is strong evidence that the upper artesian aquifers are the primary source of groundwater for the artesian spring systems in the greater Christchurch area. Therefore any pressure change in these upper aquifers will have a direct, immediate effect upon artesian spring discharge.

The relationship between artesian pressure and spring discharge was, in all cases, linear. Although analysis of the spring systems indicates high Reynolds numbers, invalidating Darcy's law, non-linear losses are negligible and it is concluded that the formation process of an artesian spring is such that losses due to turbulence are minimised.

6 Summary and Conclusions

6.1 Project Summary

6.1.1 Problem Definition

Present techniques in determining the effects of groundwater abstraction upon artesian springs do not take into account spring dynamics, which could result in the over-estimation of actual depletion induced by pumping.

Spring depletion will occur when water is intercepted and abstracted from an aquifer that supplies artesian springs, however the following questions need to be addressed:

- What is the primary source of water feeding a spring system?
- How does a spring system respond to groundwater abstraction?
- How can abstraction interference be determined and quantified?

The objective was to investigate artesian spring responses to pumping, develop a method for quantifying depletion and investigate the applicability of artesian springs as indicators of aquifer health.

6.1.2 Methodology

Theories of fluid flow in porous media were compared to data obtained from field sites in differing hydrogeological settings. The responses to abstraction were either induced directly from pumping or simulated via alteration of pressure across the artesian spring systems.

Responses in spring discharge and observations of aquifer pressures around a spring would confirm or reject the hypothesis that the shallowest artesian aquifers are the primary source of water flowing to an artesian spring system.

Correlating aquifer pressure at a spring, calculated from water level observations, with measured spring discharge would confirm or reject the hypothesis that the pressure – discharge relationship for an artesian spring is non-linear.

6.1.3 Field Data Acquisition

Field data was obtained from two test sites at Brookside and Halswell. These two sites consisted of artesian springs, occurring in differing hydrogeological environments, providing a wide range of spring data with which to test the analytical theories.

6.1.4 Interpretation of Field Data and Theoretical Analysis

Piezometer investigations indicate a change in the piezometric surface of the upper aquifer induced by the presence of a flowing artesian spring. Field results also show that pumping from the upper confined aquifer has an immediate, direct impact on spring discharge. Thus it can be concluded that the upper aquifer is the primary source of water for the spring systems studied.

Analysis of the physical set-ups of the spring sites indicates that turbulent flow is occurring at the aquifer-spring interface and in the spring fissure. Responses observed in the field, however, indicate that the effect of any turbulent losses proportional to the water velocity squared are so small that they do not significantly influence the pressure-flow interaction. As a consequence the relationship between source aquifer pressure and spring discharge is first-order and directly proportional.

6.1.5 Implication of Results

Having an entirely first-order relationship between aquifer pressure and artesian spring discharge simplifies the problem of determining the effects of pumping interference. The relationship is dependent upon spring area and aquifer parameters, however being first-order the effect of these parameters is constant throughout all observed flows and can therefore be omitted from analysis. As artesian flow is directly proportional to the pressure of the source aquifer, halving the initial artesian pressure in the aquifer will reduce spring discharge by exactly half. The current methodology employed by Environment Canterbury for determining the effects of pumping on an artesian spring is therefore consistent with what was observed during the course of this project.

Determining or estimating the impact of water mining on an artesian spring system is relatively straightforward, allowing accurate management of all gravel-based artesian spring systems in Canterbury.

6.2 Conclusions

The hypothesis that the shallow aquifer is the primary source of water for artesian springs in the greater Christchurch area has been proven to be valid. The presence of a piezometric pattern induced in the shallow aquifer by the flow of water to a spring system, along with the readily identifiable change in spring discharge upon the abstraction of water from the upper aquifer, provides strong evidence that this is the case. Interaction between the deep aquifers and artesian springs occurs indirectly and changes in deeper aquifer pressures will have a much less direct effect upon spring performance.

The hypothesis that the relationship between aquifer pressure and artesian spring flow is non-linear has been proven to be incorrect for the spring systems in Canterbury. Although theoretical analysis of flow from artesian springs indicates that turbulent flow is occurring in the artesian spring vents, field data show that losses proportional to the water velocity squared are negligible. Consequently the relationship observed between aquifer pressure and artesian spring flow is entirely first-order.

Groundwater abstraction near a spring has the following effects:

- Any pressure change in the source aquifer around an artesian spring will have an immediate effect upon spring flow.
- The magnitude of abstraction effects upon spring flow is directly proportional to the magnitude and extent of the pressure reduction. It is independent of spring characteristics and dependent only upon the hydrogeological parameters of the source aquifer.

Artesian springs are applicable as indicators of aquifer health in terms of water quality and chemical indicators of aquifer stress. In terms of water quantity, however, it is unlikely that an artesian spring will perform better than conventional water level data obtained from shallow monitoring wells.

6.3 Future Research

As little has been documented in the field of artesian spring flow, the potential for new research is particularly high. The relatively simple, empirically deduced relationship between pressure head of the source aquifers and artesian spring flow is not necessarily an indication that these systems are simple and straightforward. Indeed, approaching the problem from an analytical angle suggests otherwise. Further research in this field should include:

- Long-term correlation of groundwater levels to artesian spring flows. This data would provide further evidence of the relationships between aquifer pressure and spring discharge, especially if correlations between deeper aquifers and spring discharge can be observed.
- Comparison of discharge from free-flowing artesian wells sourced in deeper aquifers with deep aquifer pressure to determine if a non-linear relationship exists between pressure and free-flow discharge in Canterbury's deeper artesian systems.

- The effects of water mining of deeper artesian aquifers. Mining of the aquifers immediately below the shallow source aquifer may influence spring flow. The upper aquifers utilise the deeper aquifers as a source of recharge, and little is known of the pumping effects across aquitards in Canterbury.
- Dr Bruce Hunt, of the University of Canterbury, has produced an analytical solution to the problem of wells pumping in an artesian spring source aquifer. Comparison of field data with this analytical solution will ascertain its applicability for determining the effects of well interference on springs.

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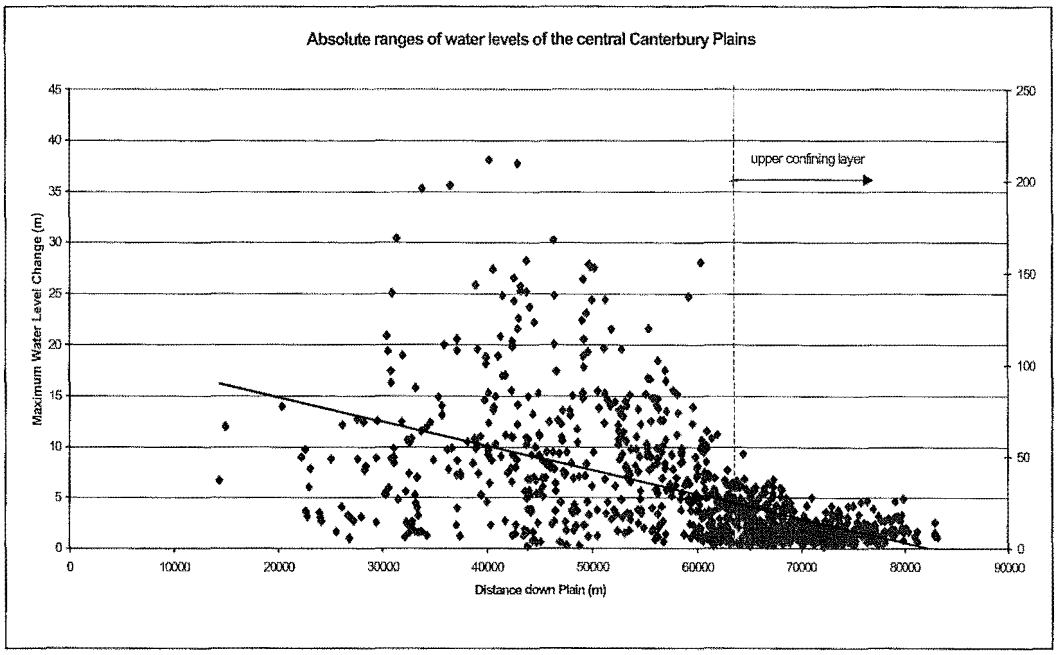
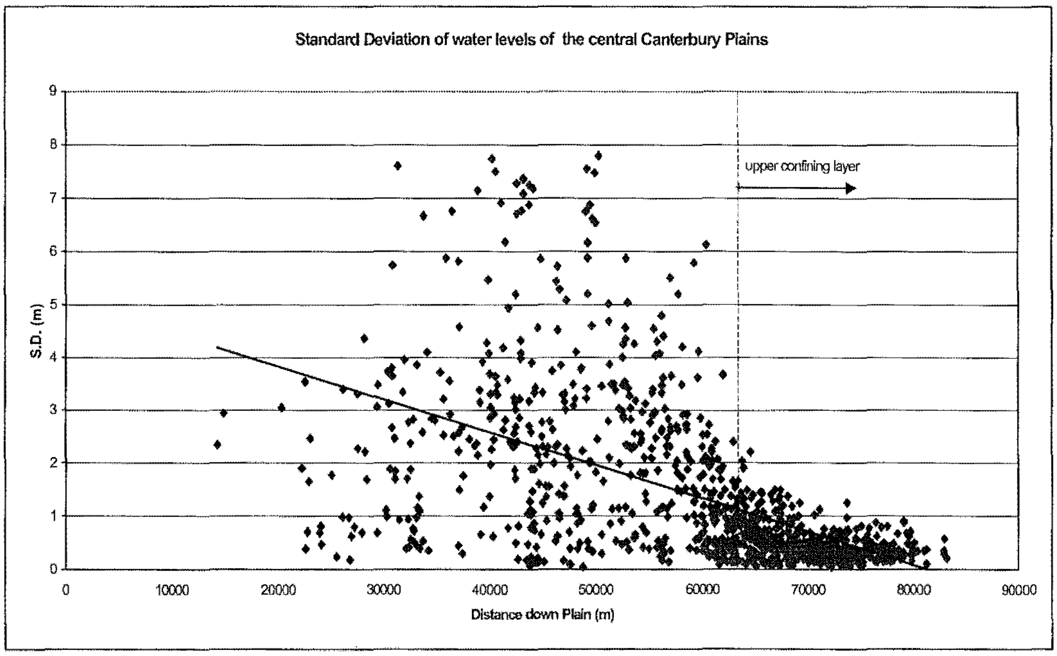
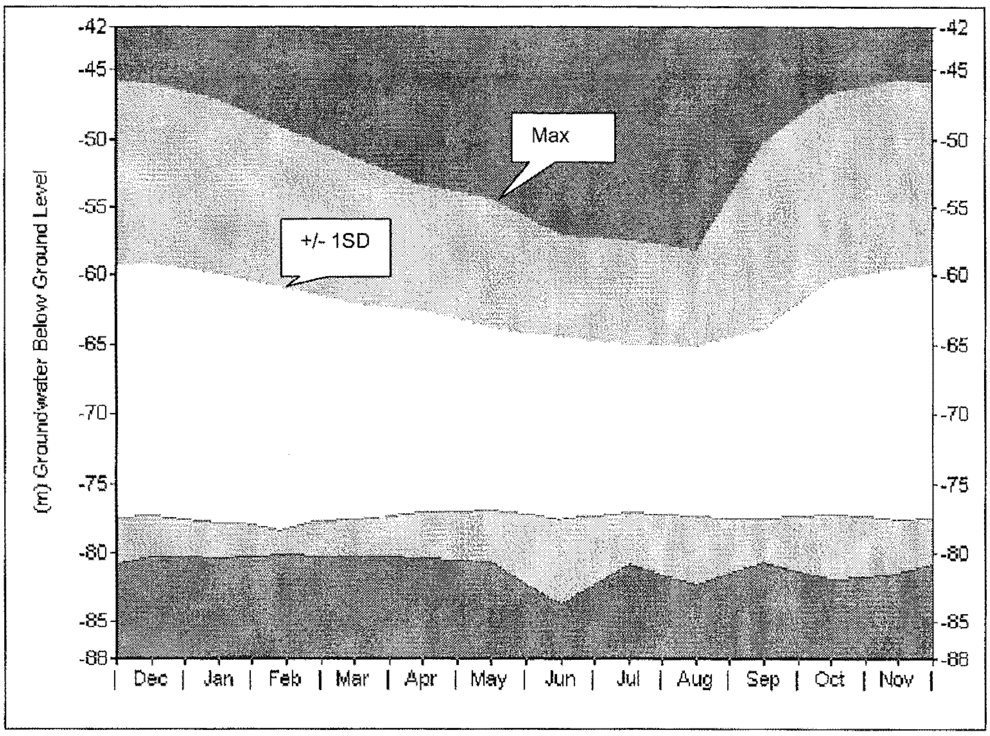
Appendix A: Canterbury Water Levels



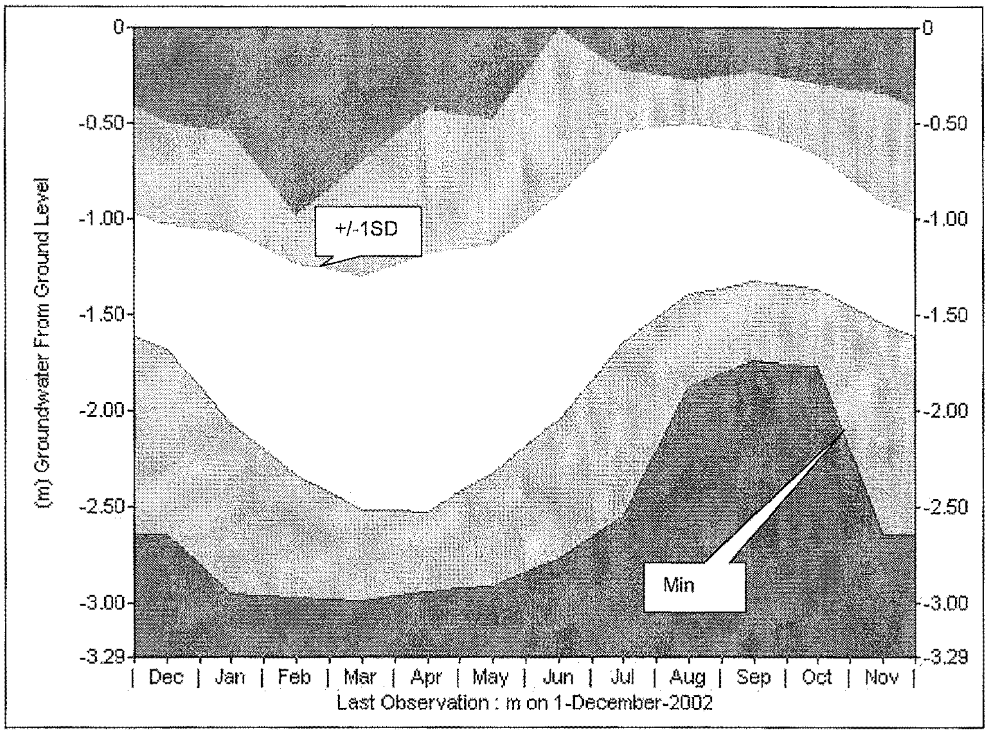
Absolute ranges of water levels of the central Canterbury Plains
Maximum Water Level Change (m)
Distance down Plain (m)
upper confining layer
0
5
10
15
20
25
30
35
40
45
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
0
50
100
150
200
250



Standard Deviation of water levels of the central Canterbury Plains
S.D. (m)
Distance down Plain (m)
upper confining layer
0
1
2
3
4
5
6
7
8
9
0
10000
20000
30000
40000
50000
60000
70000
80000
90000



Sample Groundwater Plot for M36/3167, Eastern Central Canterbury Plains



Sample Groundwater Plot for L35/0163, Upper Canterbury Plains

Appendix B: Table of Properties of Water

Physical Properties of Water in SI units

Temp °C	Density, ρ (kg/m^3)	Viscosity (Dynamic), $\mu \times 10^3$ (Pa.s)	Kinematic Viscosity, $v \times 10^6$ (m^2/s)
0	999.84	1.792	1.792
1	999.90	1.731	1.731
2	999.94	1.673	1.673
3	999.97	1.619	1.619
4	999.97	1.567	1.567
5	999.97	1.519	1.519
6	999.94	1.473	1.473
7	999.90	1.428	1.429
8	999.85	1.386	1.386
9	999.78	1.346	1.346
10	999.70	1.308	1.308
11	999.61	1.271	1.272
12	999.50	1.236	1.237
13	999.38	1.203	1.204
14	999.24	1.171	1.172
15	999.10	1.140	1.141
16	998.94	1.111	1.112
17	998.77	1.083	1.084
18	998.60	1.056	1.057
19	998.41	1.030	1.032
20	998.20	1.005	1.007
21	997.99	0.981	0.983
22	997.77	0.958	0.960
23	997.54	0.936	0.938
24	997.30	0.914	0.917
25	997.04	0.894	0.896
26	996.78	0.874	0.877
27	996.51	0.855	0.857
28	996.23	0.836	0.839
29	995.94	0.818	0.821
30	995.65	0.801	0.804
35	994.03	0.723	0.727
40	992.21	0.656	0.661
45	990.21	0.599	0.605
50	988.05	0.549	0.556

Adapted from the Handbook of Chemistry and Physics (Cleveland, Ohio: CRC Publishing Company, 1986).

Appendix C: Groundwater Models

C.1 Thiem Method (1906)

For steady-state flow that is not time dependent Thiem showed that the well discharge could be expressed by the following:

$$Q = \frac{2\pi T(s_1 - s_2)}{\ln(r_2 / r_1)} \quad \text{(C-1)}$$

where:

Q is the pumping rate (L^3/t)
s_1 and s_2 are observed drawdowns at radial distances r_1 and r_2 (L)
T is transmissivity (L^2/t)

Further assumptions for the above model to be valid are:

- The aquifer is pumped at a constant discharge rate.
- The hydraulic gradient between the pumping well and monitoring wells is at steady-state.

C.2 Theis Method (1935)

Using an analogy with heat removal from an infinite slab, Theis derived an equation to explain drawdown in piezometric surfaces due to unsteady flow to a well in a confined aquifer. This drawdown model is time-dependent, and is of the form:

$$s = \frac{Q}{4\pi T} \cdot W(u) \quad \text{(C-2)}$$

$$u = \frac{r^2 S}{4Tt} \quad \text{(C-3)}$$

where:

s is the drawdown (L)
T is transmissivity (L^2/t)
S is storativity (dimensionless)
Q is the pumping rate (L^3/t)
r is the radial distance from the pumping bore (L)
t is the duration of pumping (t)

W(u), is known as the well function and is the exponential integral $\int_u^\infty \frac{e^{-z}}{z} dz$. The value of this is given by the infinite series

$$\int_u^\infty \frac{e^{-z}}{z} dz = -0.577216 - \ln u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \frac{u^4}{4 \cdot 4!} + \cdots$$

A mathematical approximation for Microsoft Excel (Hunt, 2002) is included in section C.4

C.3 Hantush-Jacob Method (1955)

A major assumption of the Theis solution is that all the water that is abstracted is sourced from storage in the pumped aquifer. There are a number of ways in which this assumption may be compromised, for example water may enter the aquifer via leakage through aquitards, recharge from streams may occur, or water may even come from storage in the aquitards themselves. As a consequence the Theis solution may not model aquifer reactions to abstraction sufficiently accurately to be useful.

The problem of leakage has been extensively investigated by Hantush and Jacob, and an alternate solution including a leakage term is commonly used. They derived the function:

$$s = \frac{Q}{4\pi T} \cdot W\left(u, \frac{r}{\beta}\right) \qquad \text{(C-4)}$$

where:

$$u = \frac{r^2 S}{4Tt} \text{ and } \frac{r}{\beta} \text{ is the leakage coefficient.}$$

The function *W(u,r/b)* is the well function for leaky aquifers, and short-term drawdowns are described by the Theis solution and well function, *W(u)*, while long term drawdown is described by the leaky well function. A mathematical approximation for Microsoft Excel (Hunt, 2002) is included in section C.4

C.4 Visual Basic Routines

The following routines allow the approximation of well functions for Theis (1935) and Hantush-Jacob (1955) drawdown models in Microsoft Excel. All routines based on FUNCTION.XLS Visual Basic modules supplied by Dr Bruce Hunt.

Routine to compute the **Hantush leaky aquifer function** W(x,y).

$$x = u = \frac{r^2 S}{4Tt}, \; y = \frac{r}{\beta}$$

```
Function W(x, y)
If x = 0 Then
  W = 2 * BessK0(y)
Else
  R = 1
  t = y ^ 2 / (4 * x)
  b = 2 * x
  If y <= b Then
    W = 0
    n = 0
    Do
      term = R * ExpInt(n + 1, x)
      W = W + term
      n = n + 1
      R = R * (-t) / n
    Loop Until Abs(term) < 0.0000000001
  Else
    W = 2 * BessK0(y)
    n = 0
    Do
      term = R * ExpInt(n + 1, t)
      W = W - term
      n = n + 1
      R = R * (-x) / n
    Loop Until Abs(term) < 0.0000000001
  End If
End If
End Function
```

Routine to compute the exponential integral Exp1(x) for 0<x<infinity.

Exp1(x) = w(u) or **Theis well function** where $u = \dfrac{r^2 S}{4Tt}$

```
Function Exp1(x)
A0 = -0.57721566
A1 = 0.99999193
A2 = -0.24991055
A3 = 0.05519968
A4 = -0.00976004
A5 = 0.00107857
B0 = 0.2677737343
B1 = 8.6347608925
B2 = 18.059016973
B3 = 8.5733287401
```

```
B4 = 1
C0 = 3.9584969228
c1 = 21.0996530827
c2 = 25.6329561486
c3 = 9.5733223454
C4 = 1
If x <= 1 Then
  Exp1 = -Log(x) + A0 + x * (A1 + x * (A2 + x * (A3 + x * (A4 + x *
A5))))
Else
  p1 = B0 + x * (B1 + x * (B2 + x * (B3 + x * B4)))
  P2 = C0 + x * (c1 + x * (c2 + x * (c3 + x * C4)))
  Exp1 = (p1 / P2) * Exp(-x) / x
End If
End Function
```

A subroutine to compute the exponential integral of order n for n >=1.

```
Function ExpInt(n, x)
If n = 1 Then
  ExpInt = Exp1(x)
ElseIf (n > 1) And (x <= 5) Then
  a = Exp1(x)
  For I = 2 To n
    a = (Exp(-x) - x * a) / (I - 1)
  Next I
  ExpInt = a
ElseIf (n > 1) And (x > 5) Then
  N1 = Int(x)
  t = x + N1
  a = 1 + N1 / t ^ 2 + N1 * (N1 - 2 * x) / t ^ 4 + N1 * (6 * x ^ 2 - 8 * N1
* x + N1 ^ 2) / t ^ 6
  a = a * Exp(-x) / t
  If n <= N1 Then
    I = N1
    Do While I > n
      I = I - 1
      a = (Exp(-x) - I * a) / x
    Loop
    ExpInt = a
  Else
    I = N1
    Do While I < n
      I = I + 1
      a = (Exp(-x) - x * a) / (I - 1)
```

```
    Loop
    ExpInt = a
  End If
End If
End Function
```

A subroutine to compute the modified Bessel function I0(x) for 0<x<infinity.

```
Function BessI0(x)
A0 = 1
A1 = 3.5156229
A2 = 3.0899424
A3 = 1.2067492
A4 = 0.2659732
A5 = 0.0360768
A6 = 0.0045813
B0 = 0.39894228
B1 = 0.01328592
B2 = 0.00225319
B3 = -0.00157565
B4 = 0.00916281
B5 = -0.02057706
B6 = 0.02635537
B7 = -0.01647633
B8 = 0.00392377
If x <= 3.75 Then
  t = (x / 3.75) ^ 2
  BessI0 = A0 + t * (A1 + t * (A2 + t * (A3 + t * (A4 + t *
       (A5 + t * A6)))))
Else
  t = 3.75 / x
  BessI0 = B0 + t * (B1 + t * (B2 + t * (B3 + t * (B4 + t *
       (B5 + t * (B6 + t * (B7 + t * B8)))))))
  BessI0 = BessI0 * Exp(x) / Sqr(x)
End If
End Function
```

A subroutine to compute the modified Bessel function I1(x) for 0<x<infinity.

```
Function BessI1(x)
A0 = 0.5
A1 = 0.87890594
A2 = 0.51498869
A3 = 0.15084934
```

```
A4 = 0.02658733
A5 = 0.00301532
A6 = 0.00032411
B0 = 0.39894228
B1 = -0.03988024
B2 = -0.00362018
B3 = 0.00163801
B4 = -0.01031555
B5 = 0.02282967
B6 = -0.02895312
B7 = 0.01787654
B8 = -0.00420059
If x <= 3.75 Then
   t = (x / 3.75) ^ 2
   BessI1 = A0 + t * (A1 + t * (A2 + t * (A3 + t * (A4 + t * (A5 + t *
A6)))))
   BessI1 = BessI1 * x
Else
   t = 3.75 / x
   BessI1 = B0 + t * (B1 + t * (B2 + t * (B3 + t * (B4 + t * (B5 + t * (B6
+ t * (B7 + t * B8)))))))
   BessI1 = BessI1 * Exp(x) / Sqr(x)
End If
End Function
```

A subroutine to calculate the modified Bessel function K0(x) for 0<x<infinity.

```
Function BessK0(x)
A0 = -0.57721566
A1 = 0.4227842
A2 = 0.23069756
A3 = 0.0348859
A4 = 0.00262698
A5 = 0.0001075
A6 = 0.0000074
B0 = 1.25331414
B1 = -0.07832358
B2 = 0.02189568
B3 = -0.01062446
B4 = 0.00587872
B5 = -0.0025154
B6 = 0.00053208
If x <= 2 Then
   t = (x / 2) ^ 2
```

```
  BessK0 = A0 + t * (A1 + t * (A2 + t * (A3 + t * (A4 + t * (A5 + t *
A6)))))
  BessK0 = BessK0 - Application.Ln(x / 2) * BessI0(x)
Else
  t = 2 / x
  BessK0 = B0 + t * (B1 + t * (B2 + t * (B3 + t * (B4 + t * (B5 + t *
B6)))))
  BessK0 = BessK0 * Exp(-x) / Sqr(x)
End If
End Function
```

Appendix D: Drilling Logs

Borelog for well M36/6836

Gridref: M36:52910-25652
Ground Level Altitude 39 +MSD
Driller : McMillan Water Wells Ltd.
Drill Method: Rotary Rig
Drill Depth : m Drill Date : 4/08/2000

Environment Canterbury

Depth	Drillers Description	Formation
-0.30m	Earth	sp
-1.20m	Sandy gravels	sp
-2.50m	Moist sandy gravels	sp
-5.00m	Water-bearing free sandy gravels with tree roots	ri
-6.00m	Brown clay	ri
-7.30m	Claybound gravels	ri
- 10.3m	Water-bearing free gravels	ri

Scale: -5, -10

Borelog for well M36/7255

Gridref: M36:52824-25972
Ground Level Altitude 43.20303 +MSD
Driller :
Drill Method:
Drill Depth : m Drill Date :

Scale	Depth	Drillers Description	Formation
		Soil	
	-0.30m	Blue-brown clay with orange-brown silt layers	
	-1.88m	fine gravels and sand	
	-2.00m	Yellow-Orange sand - Flushed out via pumping.	
	-2.20m	fine gravels	
	-2.25m		

Borelog for well M36/7256

Gridref: M36:52832-25971
Ground Level Altitude 43.16925 +MSD
Driller : Barbar Drilling
Drill Method: Cable Tool
Drill Depth : m Drill Date : 28/06/2002

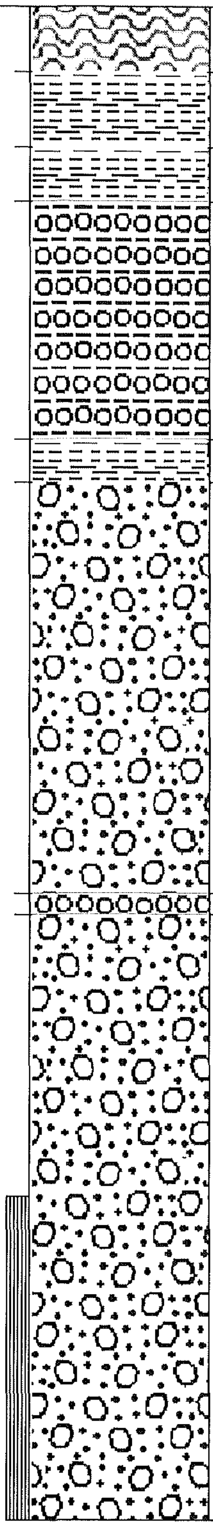
Environment Canterbury

Scale	Depth	Drillers Description	Formation
	-0.25m	Soil	
	-0.50m	Orange-brown firm plastic SILTS, flecks of grey pug layers	
	-0.80m	Orange-brown mod plastic silty SAND	
	-1.60m	Grey-blue highly plastic silty CLAY traces of orange silts	
	-2.30m	Orange-brown & grey plastic clayey SILT	
	-3.20m	Plastic silty CLAY with very weathered gravels, well rounded up to 10mm (bk/or)	
	-3.70m	Grey samll to medium water bearing GRAVELs, poorly sorted up to 30mm. Orange -Brown sand	
	-3.80m	Grey waterbearing small to medium GRAVEL with odd large grey gravel (100mm)	
	-4.90m	Grey, rounded, sorted small to medium GRAVEL slight water staining.	
-5	-5.20m	Grey, medium free GRAVELs 30-60mm minor sand	
	-6.70m	Grey-Brown small to medium free GRAVELs with intermittent sandy gravel layers. Sand inc with depth	
	-7.50m	Grey, slighly stained rounded to well rounded GRAVELs <40mm and SAND	
	-8.70m	Grey-brown small to medium free GRAVELs - collapsing & drill heave	
	-9.50m	Grey cobbles and GRAVELs 40<100mm fining with depth - WL 1m	
-10	- 10.2m	Grey-brown small GRAVELs and sand	
	- 10.3m	Yellow silt trace and gravels not drilled	

Borelog for well M36/7257

Gridref: M36:52999-25808
Ground Level Altitude 41.4182 +MSD
Driller : Barbar Drilling
Drill Method: Cable Tool
Drill Depth : m Drill Date : 1/07/2002

Environment Canterbury



Depth	Drillers Description	Formation
-0.30m	Soil	
-0.65m	Yellow-Brown dry SILTy CLAYs	
-0.90m	Brown & blue soft SILTy CLAYs	
-2.00m	Brown & blue firm SILTy CLAYs and fine brown gravels	
-2.20m	Firm blue silty CLAY with orange-brown silt layers	
-4.10m	Small to medium grey GRAVELs and grey SAND	
-4.20m	Small to medium grey GRAVELs with sand trace	
-7.00m	Samll to mediumgrey GRAVELs some stained, and brown SAND	

Scale: -5

Borelog for well M36/7258

Gridref: M36:52846-26114
Driller : Unlisted
Drill Method: Drilled then driven
Drill Depth : m Drill Date : 1/10/2002

Scale	Depth	Drillers Description	Formation
		Soil	
	-0.40m	Orange-Brown clayey SILT	
	-1.10m	Light Grey clayey SILTs	
	-2.10m	Fine GRAVELs	
	-2.30m		

Borelog for well M36/7250

Gridref: M36:76455-35808
Ground Level Altitude 12.01237 +MSD
Driller : Unlisted
Drill Method: Driven Pipe
Drill Depth : m Drill Date : 2/09/2002

Environment Canterbury

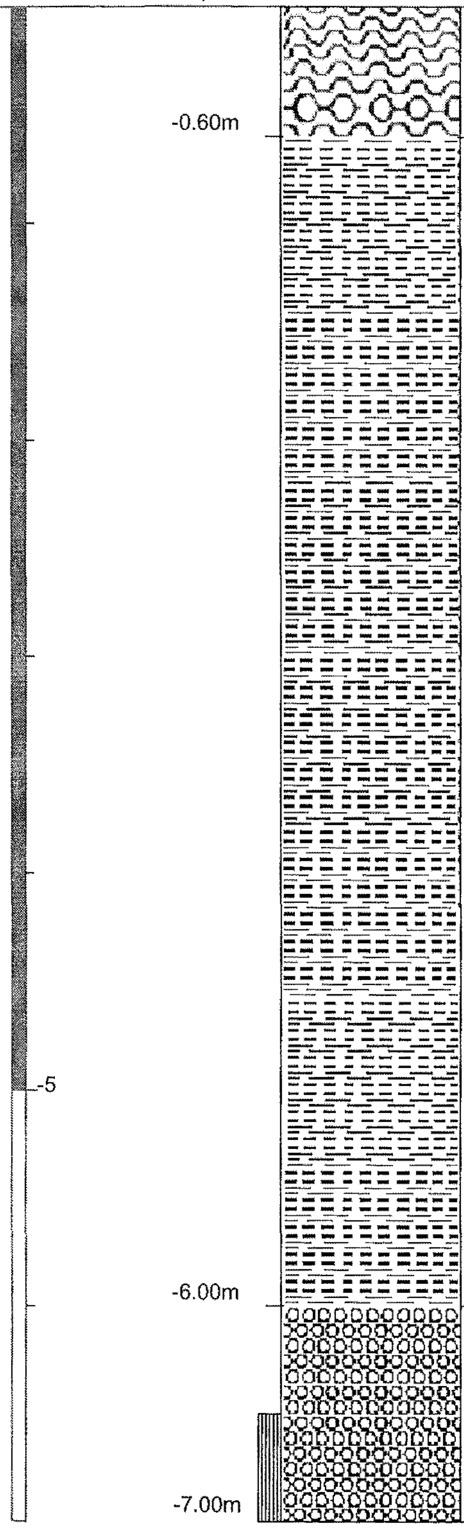
Scale	Depth	Drillers Description	Formation
		Soil	
	-0.60m	Grey silty sand and blue silty clay	
-5			
	-5.50m	Small free gravels (est depth)	
	-6.00m		

Borelog for well M36/7251

Gridref: M36:76446-35808
Ground Level Altitude 12.03469 +MSD
Driller : Unlisted
Drill Method: Driven Pipe
Drill Depth : m Drill Date : 2/09/2002

Environment Canterbury

Scale	Depth	Drillers Description	Formation
		Soil	
	-0.60m	Grey silts, clays and fine sand	
-5			
	-6.00m	Small free gravels (est depth)	
	-7.00m		



Borelog for well M36/7252

Gridref: M36:76437-35809
Ground Level Altitude 12.05398 +MSD
Driller : Unlisted
Drill Method: Driven Pipe
Drill Depth : m   Drill Date : 4/09/2002

Environment Canterbury

Scale	Depth	Drillers Description	Formation
	-0.60m	soil	
	-6.00m	Grey silts, yellow silts and black and white sand	
-5			
	-7.00m	Esitmated firm clay layer (harder driving)	
	- 10.0m	Small gravels (est depth)	

Borelog for well M36/7253

Gridref: M36:76405-35808
Ground Level Altitude 12.13636 +MSD
Driller : Unlisted
Drill Method: Driven Pipe
Drill Depth : m Drill Date : 4/09/2002

Environment Canterbury

Scale	Depth	Drillers Description	Formation
	-0.60m	soil	
	-6.00m	Grey silts, clay and very fine sand	
-5	-7.00m	Small free gravels (est depth)	

Borelog for well M36/7254

Gridref: M36:76456-35781
Ground Level Altitude 12.09359 +MSD
Driller : Unlisted
Drill Method: Driven Pipe
Drill Depth : m Drill Date : 5/09/2002

Environment Canterbury

Scale	Depth	Drillers Description	Formation
	-0.60m	Soil	
	-1.80m	Silty Clay - firm, plastic.	
	-3.90m	Traces of peaty layers, balck clay and blue-grey silty clay	
	-4.50m	Fine blue sand and silt, firming with depth	
-5	-5.00m	firm black clay and wood (ye)	
	-6.00m	Not Logged - too deep for hand auger	
	- 10.0m	Small gravels (est depth)	

Appendix E: Well Data

UNUSED M36/3547

Owner	ODELL I.G.
Street of Well	SELWYN LAKE RD
Locality	BROOKSIDE
Grid reference	M36:52912-25650 QAR 1C
Location Description	Beside pump shed of new bore M36/6836
use	
Well Status	Not Used

TRIM no	CO6C/1487
Squalarc no	
Tideda no	

Well Type	Bore or Well
Drill Date	01/07/1978
Well Depth	8.2 Measured
Depth Drilled to	0
Diameter	50
Initial Water Depth	0
Measuring Point Alt.	40.11m +MSD Interpolated ECan DTM2001
Ground Level Alt.	0.11m below MP
MP Description	Top of Casing
Driller	McMillan Water Wells Ltd.
Drilling Method	Driven Pipe
Casing Material	STEEL
Pump Type	Centrifugal (Surface)
Pump Set at	m -GL
Yield	0
Drawdown	0
Hours Pumped	0
Specific Capacity	
Aquifer Type	Unknown
Aquifer Name	
Aquifer Thickness	0 Multiple Aq :
Welldepth in Aquifer	0

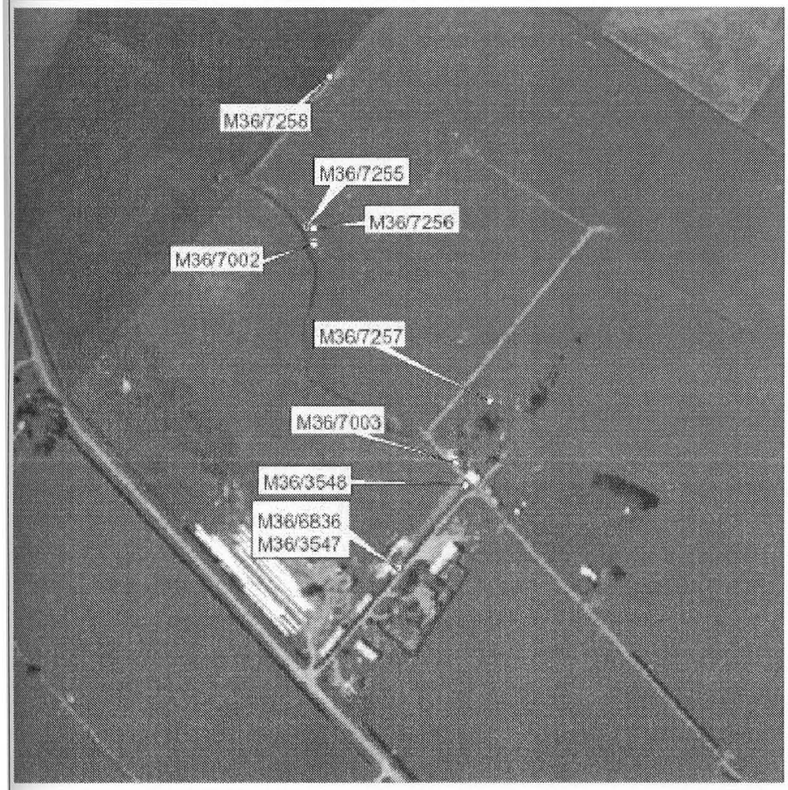
Reading Count	19
Strata Logs	0
Aquifer Test	0
Isotope Data	0
Geophysical	N
Fossil data	

Screen

Screen Type	
Top -GL	0
Bottom -GL	0
ScreenType	
Top -GL	0
Bottom -GL	0

Highest GWL	-1.13
Lowest GWL	-2.67
First reading	25/04/2001
Last reading	21/10/2002
Calc. min. GWL	0.1
Last Updated	12/02/2002
Update LogonID	MarcE
Last Field Check	12/02/2002
Printed on	20/02/2003 09:51p.m.

MarcE	12/02/2002	The old well has been capped but still accessible.
JACQUELINE	10/08/2000	Bore to be replaced by M36/6836.



WELL M36/3548

Owner : ODELL I.G.
Street of Well : SELWYN LAKE RD
Locality : BROOKSIDE
Grid reference : M36:52976-25727 QAR 1C
Location Description : SEE also M36/3547

use : Irrigation

TRIM no : CO6C/1487
Squalarc no :
Tideda no :
GW Consent no : NCY890526A 30.0l/s

Environment Canterbury
Your regional council

Well Type : Bore or Well
Drill Date : 01/07/1972
Well Depth : 13.1 Reported
Depth Drilled to : 0
Diameter : 158
Initial Water Depth : 0

Measuring Point Alt.: 40.48m +MSD Interpolated ECan DTM2001
Ground Level Alt. : same as MP
MP Description :

Driller : McMillan Water Wells Ltd.
Drilling Method : Cable Tool
Casing Material : STEEL
Pump Type : Centrifugal (Surface)
Pump Set at : m -GL
Yield :
Drawdown :
Hours Pumped :
Specific Capacity :

Aquifer Type : Unknown
Aquifer Name :
Aquifer Thickness : 0 Multiple Aq :
Welldepth in Aquifer: 0

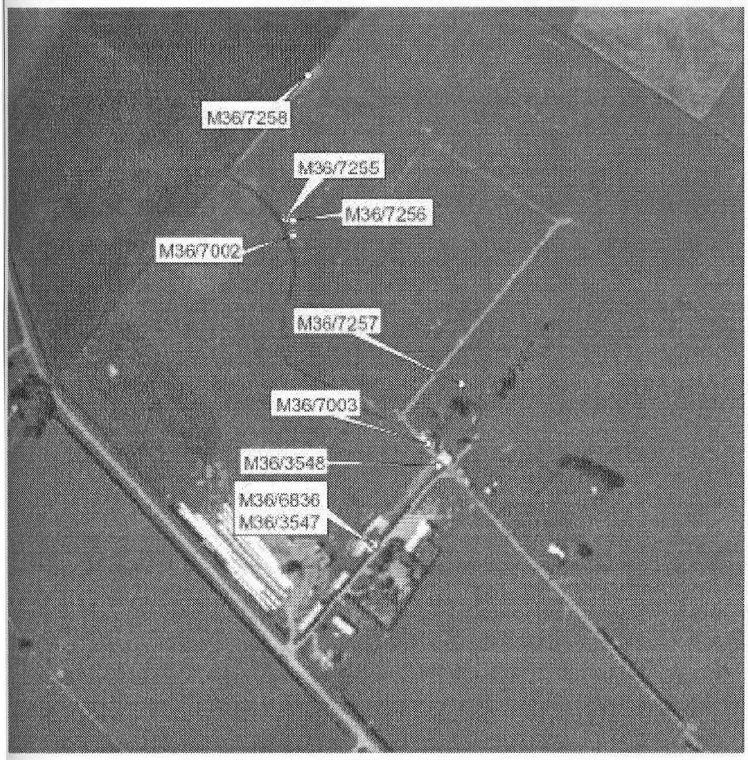
Reading Count : 0
Strata Logs : 0
Aquifer Test : 1
Isotope Data : 0
Geophysical : N
Fossil data :

Screen
Screen Type :
Top -GL : 0
Bottom -GL : 0
ScreenType:
Top -GL : 0
Bottom -GL : 0

Last Updated : 09/10/2001
Update LogonID : marce
Last Field Check: 27/06/2001
Printed on : 20/02/2003 09:51p.m.

marce 09/10/2001 Adjusted Gridref after field visit.

Aquifer test conducted with this well pumping for two days.
3/7/01



WELL M36/6836

Owner : Odell, IG and A
Street of Well : Selwyn Lake Road
Locality : Brookside
Grid reference : M36:52910-25652 QAR 1C
Location Description : 2m west of M36/3547 in shed.

use : Domestic Supply
use : Stock Supply
use : Dairy Use

TRIM no : C06C/1487
Squalarc no :
Tideda no :

Well Type : Bore or Well
Drill Date : 04/08/2000
Well Depth : 10.34 Measured
Depth Drilled to :
Diameter : 100
Initial Water Depth : -1.5

Measuring Point Alt.: 39.3m +MSD From DTM by LEnv
Ground Level Alt. : 0.3m below MP
MP Description : shed floor

Driller : McMillan Water Wells Ltd.
Drilling Method : Rotary Rig
Casing Material :
Pump Type :
Pump Set at : m -GL
Yield : 6
Drawdown : 1.13
Hours Pumped : 0.75
Specific Capacity : 5.31

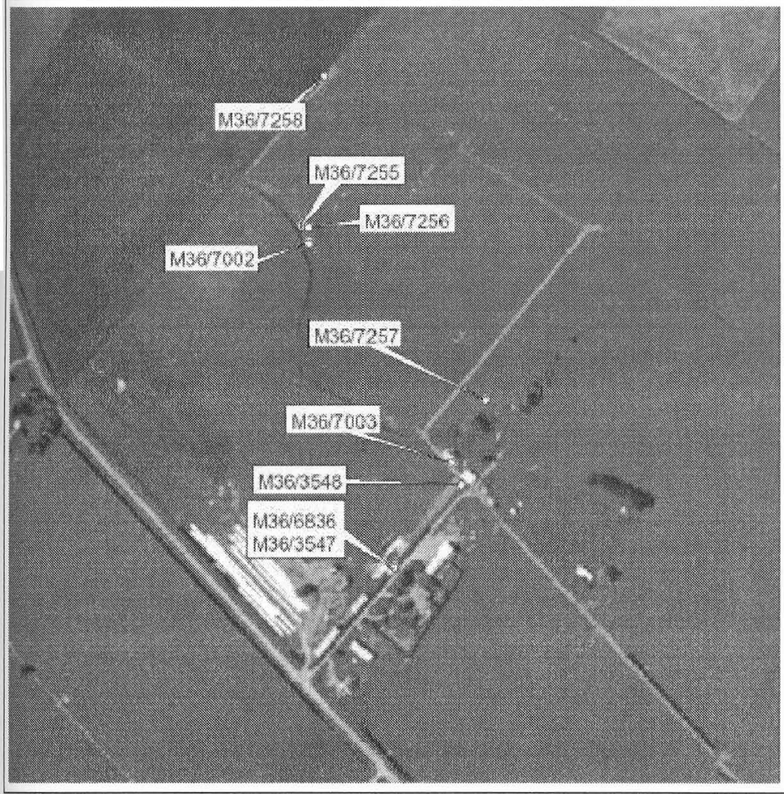
Aquifer Type :
Aquifer Name : Riccarton Gravel
Aquifer Thickness : Multiple Aq :
Welldepth in Aquifer:

Reading Count : 1
Strata Logs : 7
Aquifer Test : 0
Isotope Data : 0
Geophysical : N
Fossil data : N

Screen
Screen Type : Stainless steel
Top -GL : 9.34
Bottom -GL : 10.34

Water Level : -2.52
Measured on : 27/06/2001
Last Updated : 06/07/2001
Update LogonID : MattS
Last Field Check: 27/06/2001
Printed on : 20/02/2003 09:51p.m.

marce 02/07/2001 noted in application that this bore is being installed to replace M36/3547



UNUSED M36/7002

Owner	ODELL I.G.
Street of Well	Selwyn Lake Road
Locality	Brookside
Grid reference	M36:52832-25956 QAR 1C
Location Description	Pipe in spring area M36/5796
use	
Well Status	Not Used

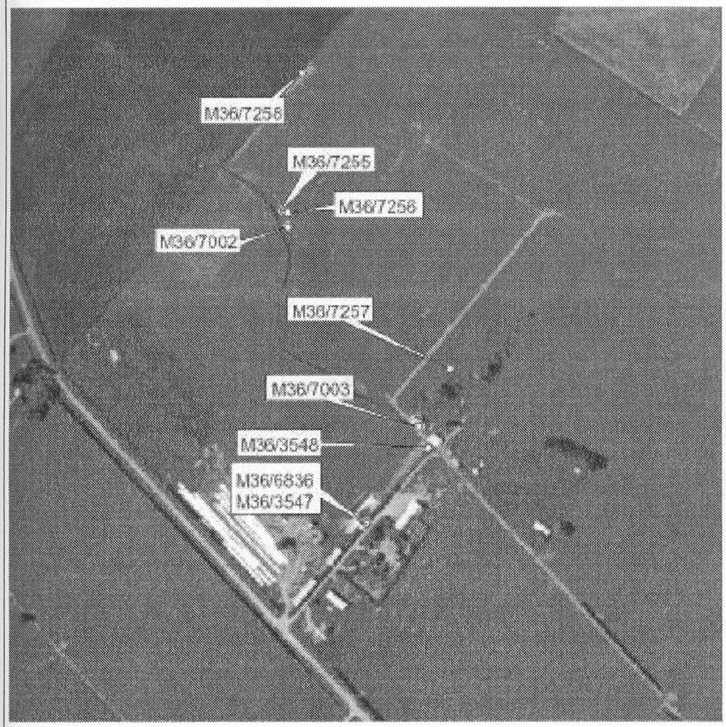
Environment Canterbury
Your regional council

TRIM no	C06C/1487
Squalarc no	
Tideda no	6367002

Well Type	Bore or Well
Drill Date	
Well Depth	1.7 Measured
Depth Drilled to	
Diameter	50
Initial Water Depth	
Measuring Point Alt.	42.6m +MSD From DTM by LEnv
Ground Level Alt.	0.6m below MP
MP Description	Top of casing
Driller	
Drilling Method	
Casing Material	
Pump Type	
Pump Set at	m -GL
Yield	
Drawdown	
Hours Pumped	
Specific Capacity	
Aquifer Type	
Aquifer Name	
Aquifer Thickness	Multiple Aq :
Welldepth in Aquifer	

Reading Count	17
Strata Logs	0
Aquifer Test	0
Isotope Data	0
Geophysical	
Fossil data	
Screen	
Screen Type	
Top -GL	
Bottom -GL	
Highest GWL	-0.11
Lowest GWL	-1.7
First reading	25/04/2001
Last reading	21/10/2002
Calc. min. GWL	0.2
Last Updated	30/01/2003
Update LogonID	MattS
Last Field Check	27/06/2001
Printed on	20/02/2003 09:51p.m.

marce	09/10/2001	Very old pipe possibly deeper but filled up over time. It seems to be connected to same aquifer as M36/3548 is pumping from. Windmill long gone.
marce	03/07/2001	Used as observation well for pump test on M36/3548 (3/7/01)



UNUSED M36/7003

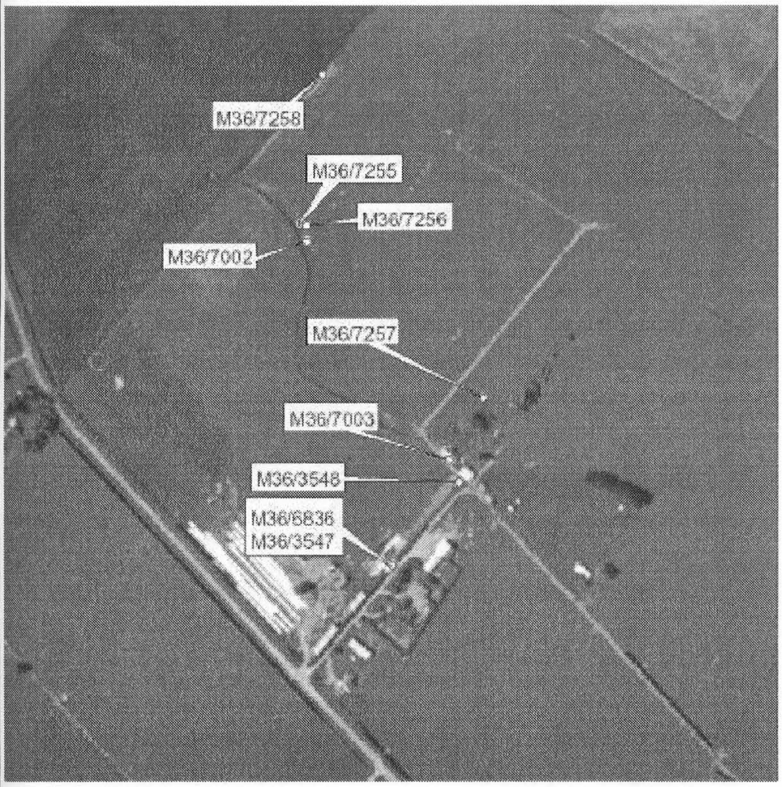
Owner	ODELL I.G.
Street of Well	Selwyn Lake Road
Locality	Brookside
Grid reference	M36:52966-25749 QAR 1C
Location Description	Pipe at side of old dairy shed
use	
Well Status	Not Used

TRIM no	CO6C/1487
Squalarc no	
Tideda no	6367003

Well Type	Bore or Well
Drill Date	
Well Depth	5.5 Measured
Depth Drilled to	
Diameter	50
Initial Water Depth	
Measuring Point Alt.	40.1m +MSD From DTM by LEnv
Ground Level Alt.	0.1m below MP
MP Description	top of casing
Driller	
Drilling Method	
Casing Material	
Pump Type	
Pump Set at	m -GL
Yield	
Drawdown	
Hours Pumped	
Specific Capacity	
Aquifer Type	
Aquifer Name	
Aquifer Thickness	Multiple Aq :
Welldepth in Aquifer	

Reading Count	17
Strata Logs	0
Aquifer Test	0
Isotope Data	0
Geophysical	
Fossil data	
Screen	
Screen Type	
Top -GL	
Bottom -GL	
Highest GWL	-1.01
Lowest GWL	-2.32
First reading	02/07/2001
Last reading	13/03/2003
Calc. min. GWL	0
Last Updated	15/11/2001
Update LogonID	marce
Last Field Check	27/06/2001
Printed on	20/02/2003 09:51p.m.

marce 09/10/2001 Used as observation bore in aquifer test on well M36/3548 (3/7/01)



WELL M36/7255

Owner	ENVIRONMENT CANTERBURY
Street of Well	SELWYN LAKE RD
Locality	BROOKSIDE
Grid reference	M36:52824-25972 QAR 1C
Location Description	
use	Aquifer Testing

TRIM no	C06C/19422
Squalarc no	
Tideda no	

Well Type	Bore or Well
Drill Date	
Well Depth	2.25 Measured
Depth Drilled to	
Diameter	80
Initial Water Depth	
Measuring Point Alt.	43.2m +MSD Interpolated ECan DTM2003
Ground Level Alt.	same as MP
MP Description	
Driller	
Drilling Method	
Casing Material	
Pump Type	
Pump Set at	m -GL
Yield	
Drawdown	
Hours Pumped	
Specific Capacity	
Aquifer Type	
Aquifer Name	
Aquifer Thickness	Multiple Aq :
Welldepth in Aquifer	

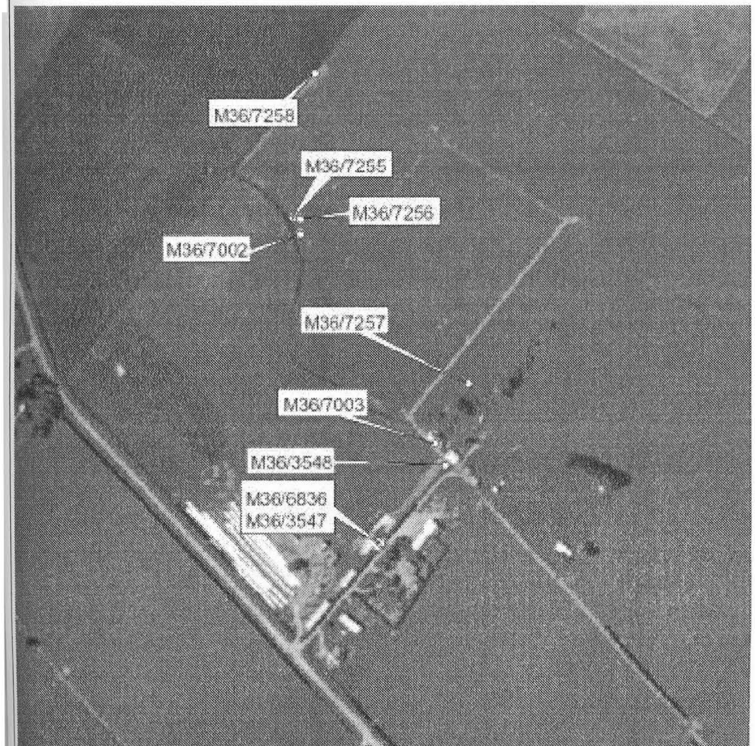
Reading Count	0
Strata Logs	5
Aquifer Test	0
Isotope Data	0
Geophysical	
Fossil data	

Screen

Screen Type	Slotted Casing
Top -GL	
Bottom -GL	

Last Updated	17/12/2002
Update LogonID	MattS
Last Field Check	
Printed on	20/02/2003 09:51p.m.

suzanneg 11/06/2002 To install, both pumping and monitoring, bores to investigate the influences of groundwater abstraction effects upon artesian spring flow.



WELL M36/7256

Owner : ENVIRONMENT CANTERBURY
Street of Well : SELWYN LAKE ROAD
Locality : BROOKSIDE
Grid reference : M36:52832-25971 QAR 1C
Location Description :

use : Water Level Observation

TRIM no : CO6C/19421
Squalarc no :
Tideda no :

Well Type : Bore or Well
Drill Date : 28/06/2002
Well Depth : 10.2 Measured
Depth Drilled to :
Diameter : 152
Initial Water Depth :

Measuring Point Alt.: 43.17m +MSD Interpolated ECan DTM2003
Ground Level Alt. : same as MP
MP Description :

Driller : Barbar Drilling
Drilling Method : Cable Tool
Casing Material : STEEL
Pump Type :
Pump Set at : m -GL
Yield :
Drawdown :
Hours Pumped :
Specific Capacity :

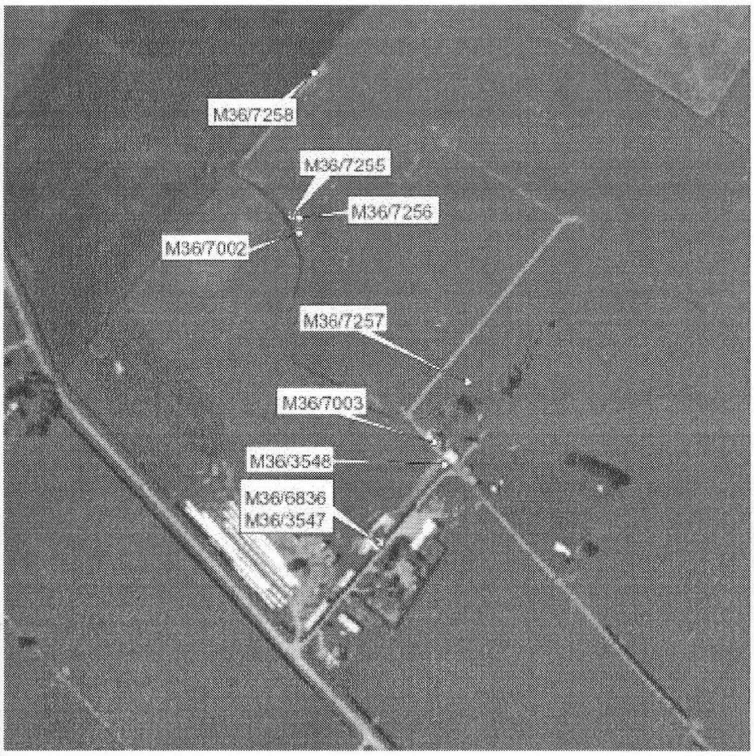
Aquifer Type :
Aquifer Name :
Aquifer Thickness : Multiple Aq :
Welldepth in Aquifer:

Reading Count : 0
Strata Logs : 16
Aquifer Test : 0
Isotope Data : 0
Geophysical :
Fossil data :

Screen
Screen Type : Slotted Casing
Top -GL : 8
Bottom -GL : 10

Last Updated : 30/01/2003
Update LogonID : MattS
Last Field Check:
Printed on : 20/02/2003 09:51p.m.

suzanneg 11/06/2002 To install both pumping and monitoring, bores to investigate the influences of groundwater abstraction effects upon artesian spring flow.



WELL M36/7257

Owner : ENVIRONMENT CANTERBURY
Street of Well : SELWYN LAKE ROAD
Locality : BROOKSIDE
Grid reference : M36:52999-25808 QAR 2
Location Description :

use : Water Level Observation

TRIM no : CO6C/19421
Squalarc no :
Tideda no :

Well Type : Bore or Well
Drill Date : 01/07/2002
Well Depth : 7.5 Measured
Depth Drilled to :
Diameter : 152
Initial Water Depth :

Measuring Point Alt.: 41.42m +MSD Interpolated ECan DTM2003
Ground Level Alt. : same as MP
MP Description :

Driller : Barbar Drilling
Drilling Method : Cable Tool
Casing Material : STEEL
Pump Type :
Pump Set at : m -GL
Yield :
Drawdown :
Hours Pumped :
Specific Capacity :

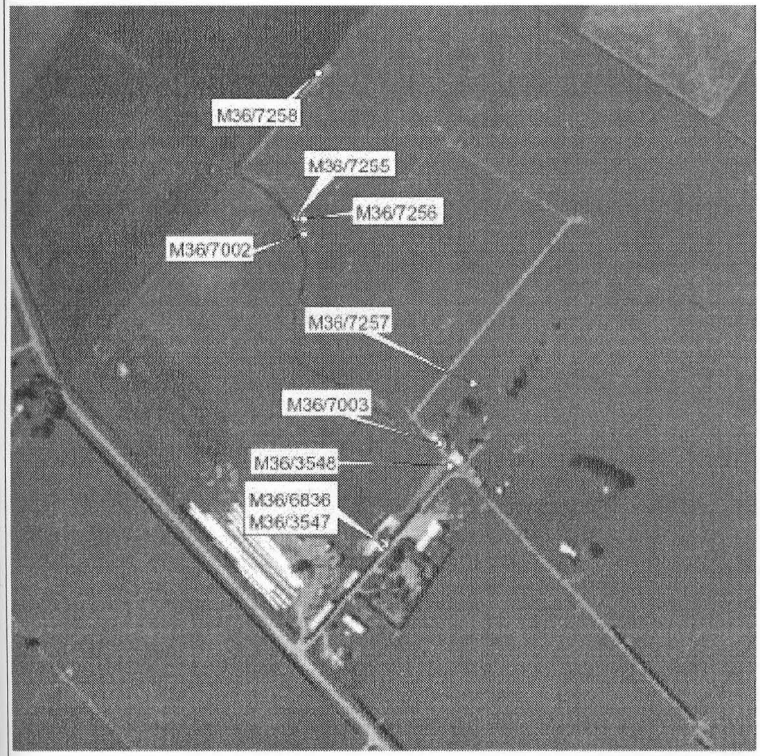
Aquifer Type :
Aquifer Name :
Aquifer Thickness : Multiple Aq :
Welldepth in Aquifer:

Reading Count : 0
Strata Logs : 8
Aquifer Test : 0
Isotope Data : 0
Geophysical :
Fossil data :

Screen
Screen Type : Slotted Casing
Top -GL : 5.5
Bottom -GL : 7.5

Last Updated : 24/01/2003
Update LogonID : MattS
Last Field Check:
Printed on : 20/02/2003 09:52p.m.

suzanneg 11/06/2002 To install both pumping and monitoring, bores to investigate the influences of groundwater abstraction effects upon artesian spring flow.



WELL M36/7258

Owner : ENVIRONMENT CANTERBURY
Street of Well : SELWYN LAKE ROAD
Locality : BROOKSIDE
Grid reference : M36:52846-26114 QAR 1C
Location Description :

use : Aquifer Testing

TRIM no : C06C/19421
Squalarc no :
Tideda no :

Well Type	Bore or Well	Reading Count	0
Drill Date	01/10/2002	Strata Logs	4
Well Depth	2.4 Measured	Aquifer Test	0
Depth Drilled to		Isotope Data	0
Diameter	30	Geophysical	
Initial Water Depth		Fossil data	

Measuring Point Alt. :
Ground Level Alt. :
MP Description :

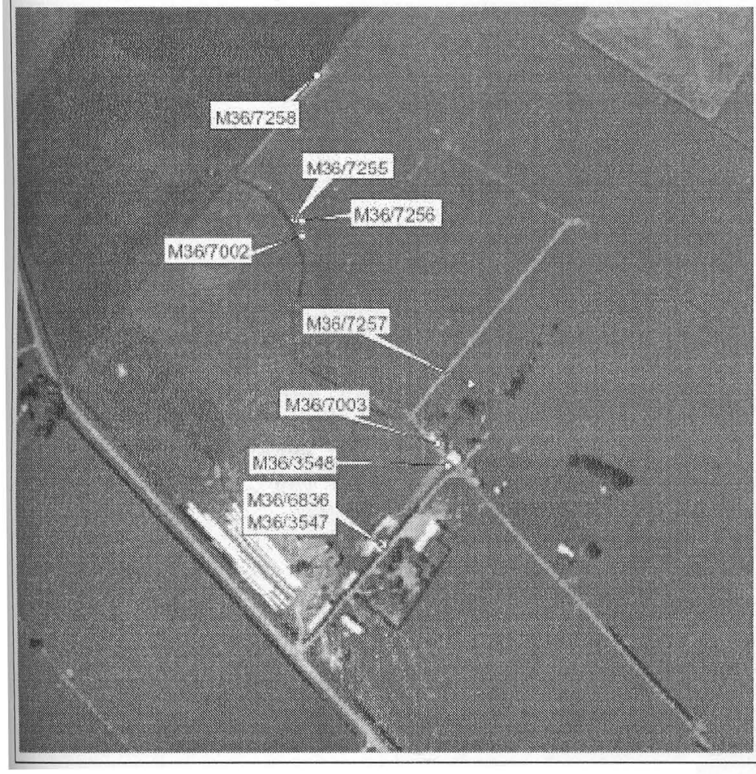
Screen
Screen Type : Drilled Holes
Top -GL :
Bottom -GL :

Driller : Unlisted
Drilling Method : Drilled then driven
Casing Material : PVC
Pump Type :
Pump Set at : m -GL
Yield :
Drawdown :
Hours Pumped :
Specific Capacity :

Last Updated : 17/12/2002
Update LogonID : MattS
Last Field Check:
Printed on : 20/02/2003 09:52p.m.

Aquifer Type :
Aquifer Name :
Aquifer Thickness : Multiple Aq :
Welldepth in Aquifer:

suzanneg 11/06/2002 To install both pumping and monitoring, bores to investigate the influences of groundwater abstraction effects upon artesian spring flow.



UNUSED M36/1938

Owner	Tripple Treasures Co.
Street of Well	484 CASHMERE RD
Locality	CASHMERE
Grid reference	M36:76499-35940 QAR 1C
Location Description	U shaped pipe in paddock to Nth of stock race
use	
Well Status	Not Used
TRIM no	
Squalarc no	
Tideda no	

Well Type	Bore or Well
Drill Date	01/07/1900
Well Depth	12 Reported
Depth Drilled to	0
Diameter	50
Initial Water Depth	0
Measuring Point Alt.	11.56m +MSD Interpolated ECan DTM2003
Ground Level Alt.	same as MP
MP Description	
Driller	not known
Drilling Method	Driven Pipe
Casing Material	STEEL
Pump Type	None Installed
Yield	0
Drawdown	0
Hours Pumped	0
Specific Capacity	
Aquifer Type	Unknown
Aquifer Name	
Aquifer Thickness	0 Multiple Aq :
Welldepth in Aquifer	0

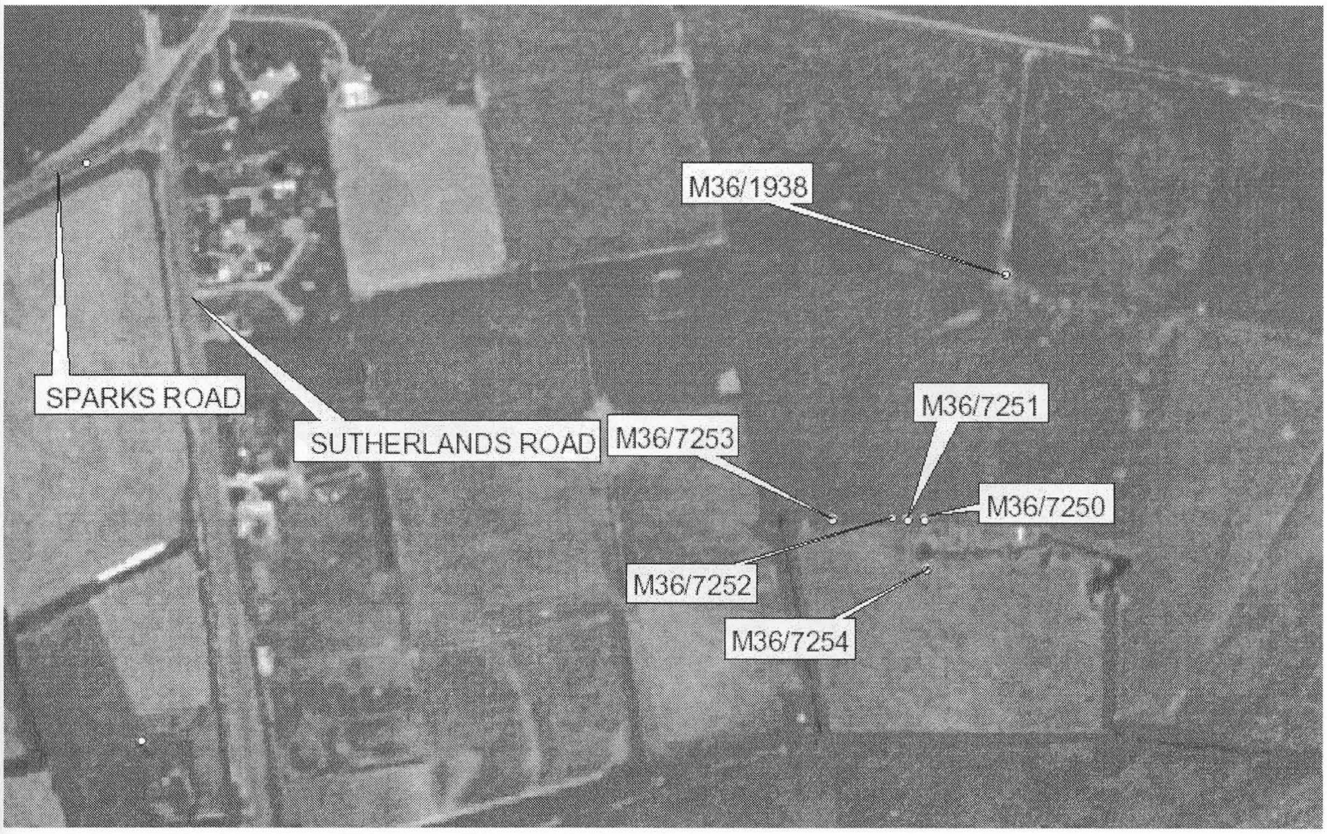
Reading Count	0
Strata Logs	0
Aquifer Test	0
Isotope Data	0
Geophysical	N
Fossil data	

Screen

Screen Type	
Top -GL	0
Bottom -GL	0
ScreenType	
Top -GL	0
Bottom -GL	0

Last Updated	11/09/2002
Update LogonID	MattS
Last Field Check	
Printed on	21/01/2003 03:52p.m.

MattS	11/09/2002	Flowing artesian , Capped
MattS	11/09/2002	Gridref changed from: M36:765-359



WELL M36/7250

Owner : ENVIRONMENT CANTERBURY
Street of Well : 600 CASHMERE ROAD
Locality : CASHMERE
Grid reference : M36:76455-35808 QAR 1C
Location Description :

use : Aquifer Testing

TRIM no : CO6C/19422
Squalarc no :
Tideda no :

Well Type : Bore or Well
Drill Date : 02/09/2002
Well Depth : 6 Measured
Depth Drilled to :
Diameter : 62
Initial Water Depth :

Measuring Point Alt.: 12.01m +MSD Interpolated ECan DTM2003
Ground Level Alt. : same as MP
MP Description :

Driller : Unlisted
Drilling Method : Driven Pipe
Casing Material : STEEL
Pump Type :
Pump Set at : m -GL
Yield :
Drawdown :
Hours Pumped :
Specific Capacity :

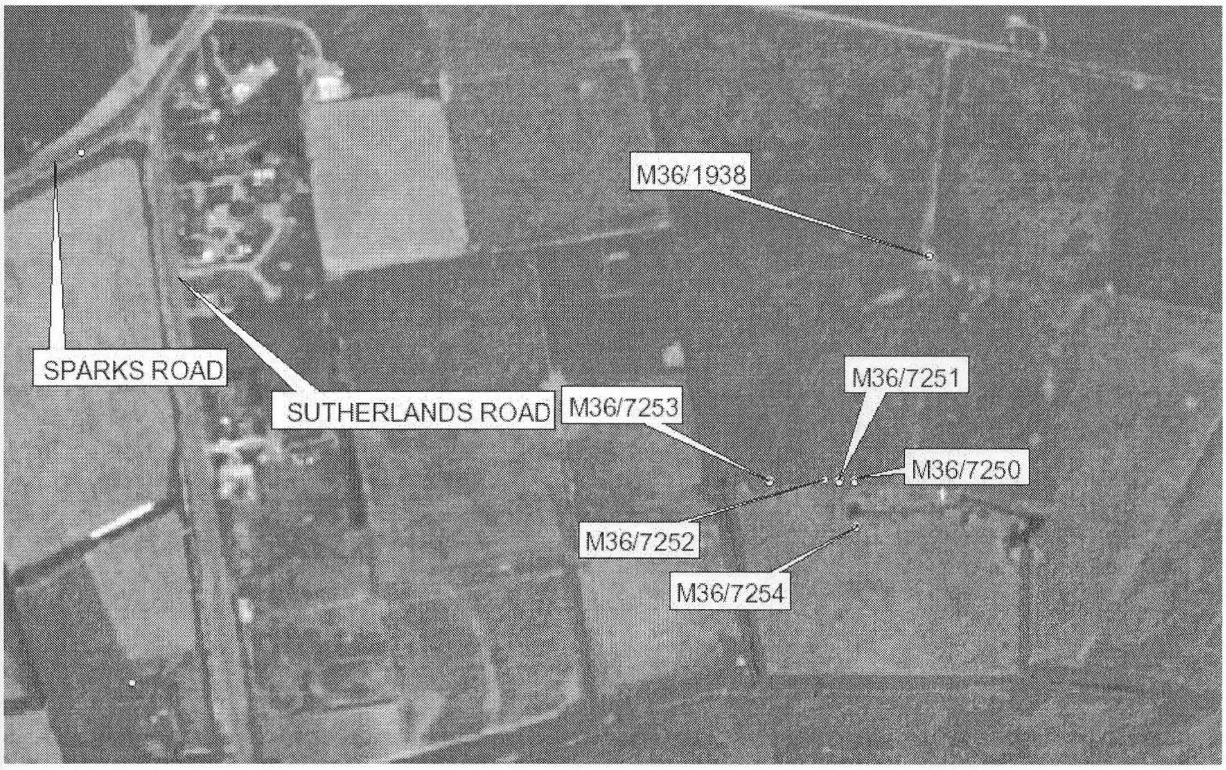
Aquifer Type :
Aquifer Name :
Aquifer Thickness : Multiple Aq :
Welldepth in Aquifer:

Reading Count : 0
Strata Logs : 3
Aquifer Test : 0
Isotope Data : 0
Geophysical :
Fossil data :

Screen
Screen Type : Drilled Holes
Top -GL : 5.5
Bottom -GL : 6

Last Updated : 30/01/2003
Update LogonID : MattS
Last Field Check:
Printed on : 21/01/2003 03:52p.m.

MattS 30/01/2003	Borelog estimated from flushing residue - See M36/7254
suzanneg 11/06/2002	To install, both pumping and monitoring, bores to investigate the influences of groundwater abstraction effects upon artesian spring flow.



WELL M36/7251

Owner	ENVIRONMENT CANTERBURY
Street of Well	600 CASHMERE ROAD
Locality	CASHMERE
Grid reference	M36:76446-35808 QAR 1C
Location Description	
use	Aquifer Testing

TRIM no	C06C/19422
Squalarc no	
Tideda no	

Well Type	Bore or Well
Drill Date	02/09/2002
Well Depth	7 Measured
Depth Drilled to	
Diameter	62
Initial Water Depth	
Measuring Point Alt.	12.03m +MSD Interpolated ECan DTM2003
Ground Level Alt.	same as MP
MP Description	
Driller	Unlisted
Drilling Method	Driven Pipe
Casing Material	STEEL
Pump Type	
Pump Set at	m -GL
Yield	
Drawdown	
Hours Pumped	
Specific Capacity	
Aquifer Type	
Aquifer Name	
Aquifer Thickness	Multiple Aq :
Welldepth in Aquifer	

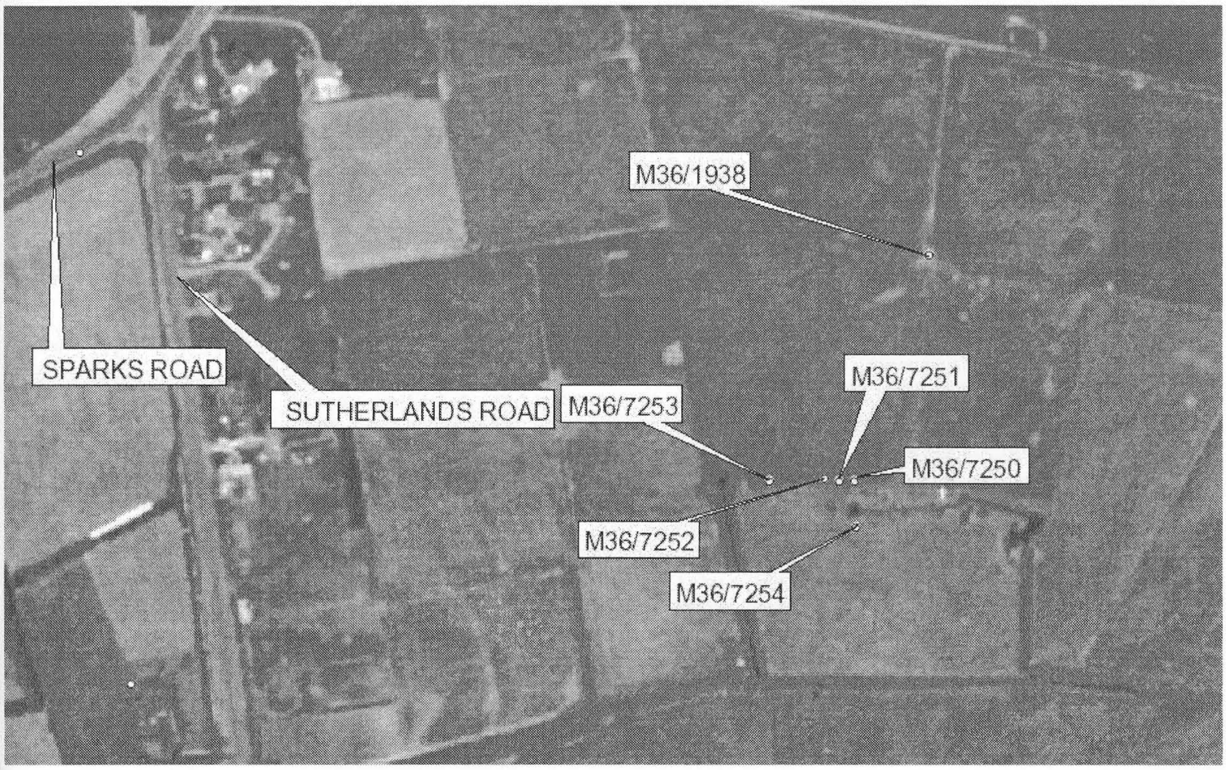
Reading Count	0
Strata Logs	3
Aquifer Test	0
Isotope Data	0
Geophysical	
Fossil data	

Screen

Screen Type	Drilled Holes
Top -GL	6.5
Bottom -GL	7

Last Updated	30/01/2003
Update LogonID	MattS
Last Field Check	
Printed on	21/01/2003 03:52p.m.

MattS 30/01/2003	Borelog estimated from flushing residue - See M36/7254
suzanneg 11/06/2002	To install, both pumping and monitoring, bores to investigate the influences of groundwater abstraction effects upon artesian spring flow.



WELL M36/7252

Owner : ENVIRONMENT CANTERBURY
Street of Well : 600 CASHMERE ROAD
Locality : CASHMERE
Grid reference : M36:76437-35809 QAR 1C
Location Description :

use : Aquifer Testing

TRIM no : CO6C/19422
Squalarc no :
Tideda no :

Environment Canterbury
Your regional council

Well Type : Bore or Well
Drill Date : 04/09/2002
Well Depth : 10 Measured
Depth Drilled to :
Diameter : 62
Initial Water Depth :

Measuring Point Alt.: 12.05m +MSD Interpolated ECan DTM2003
Ground Level Alt. : same as MP
MP Description :

Driller : Unlisted
Drilling Method : Driven Pipe
Casing Material : STEEL
Pump Type :
Pump Set at : m -GL
Yield :
Drawdown :
Hours Pumped :
Specific Capacity :

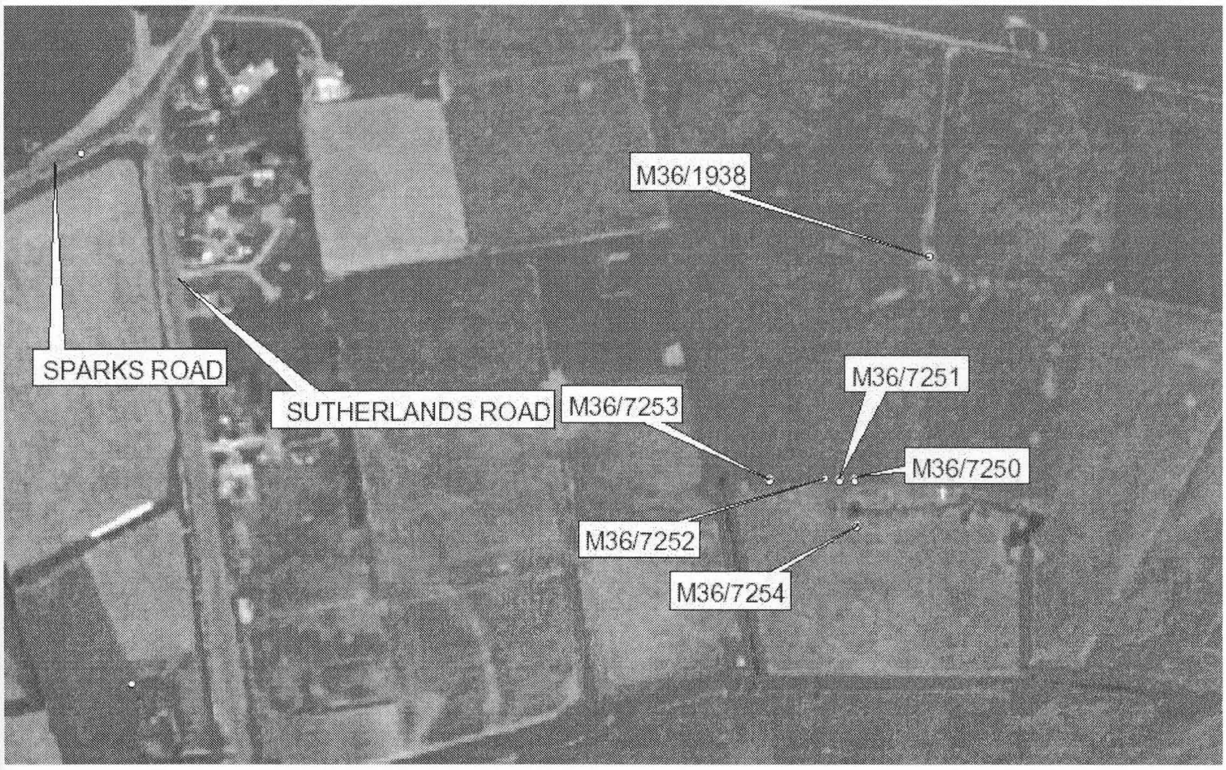
Aquifer Type :
Aquifer Name :
Aquifer Thickness : Multiple Aq :
Welldepth in Aquifer:

Reading Count : 0
Strata Logs : 4
Aquifer Test : 0
Isotope Data : 0
Geophysical :
Fossil data :

Screen
Screen Type : Drilled Holes
Top -GL : 8
Bottom -GL : 10

Last Updated : 30/01/2003
Update LogonID : MattS
Last Field Check:
Printed on : 21/01/2003 03:53p.m.

MattS 30/01/2003	Borelog estimated from flushing residue - See M36/7254
suzanneg 11/06/2002	To install, both pumping and monitoring, bores to investigate the influences of groundwater abstraction effects upon artesian spring flow.



WELL M36/7253

Owner : ENVIRONMENT CANTERBURY
Street of Well : 600 CASHMERE ROAD
Locality : CASHMERE
Grid reference : M36:76405-35808 QAR 1C
Location Description :

use : Aquifer Testing

TRIM no : CO6C/19422
Squalarc no :
Tideda no :

Well Type : Bore or Well
Drill Date : 04/09/2002
Well Depth : 7 Measured
Depth Drilled to :
Diameter : 62
Initial Water Depth :

Measuring Point Alt.: 12.14m +MSD Interpolated ECan DTM2003
Ground Level Alt. : same as MP
MP Description :

Driller : Unlisted
Drilling Method : Driven Pipe
Casing Material : STEEL
Pump Type :
Pump Set at : m -GL
Yield :
Drawdown :
Hours Pumped :
Specific Capacity :

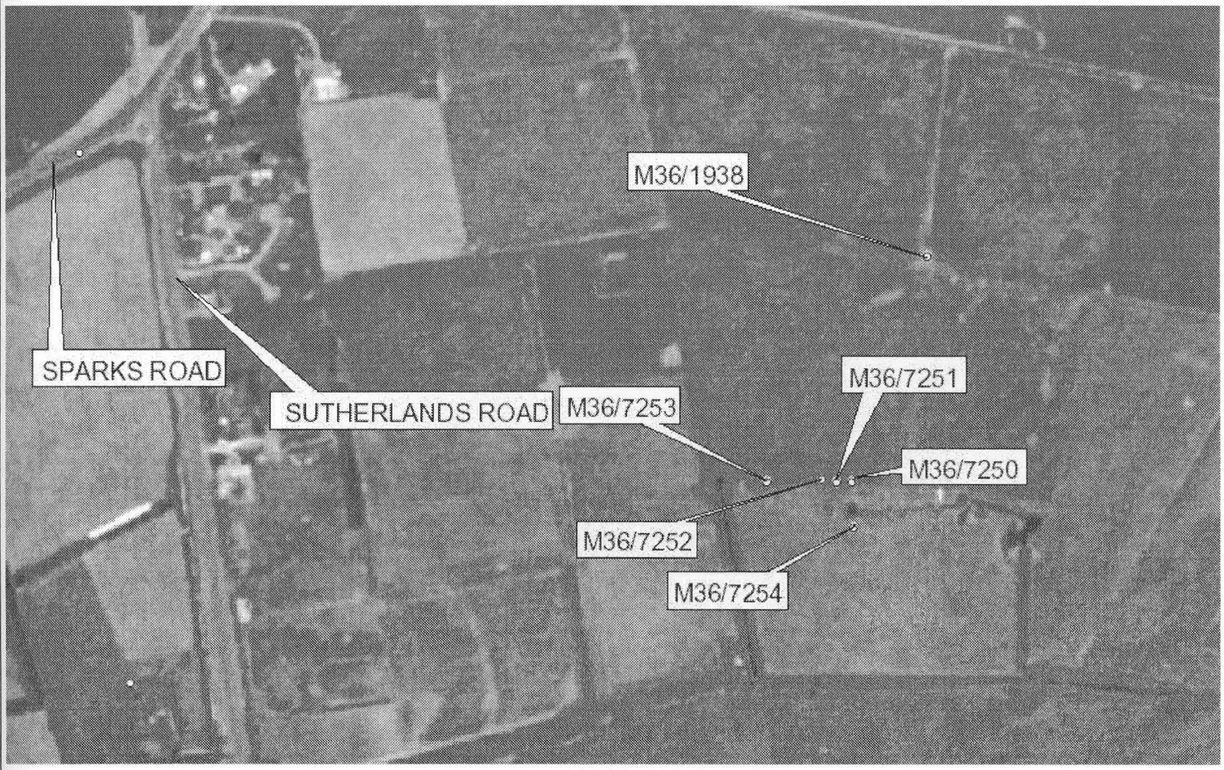
Aquifer Type :
Aquifer Name :
Aquifer Thickness : Multiple Aq :
Welldepth in Aquifer:

Reading Count : 0
Strata Logs : 3
Aquifer Test : 0
Isotope Data : 0
Geophysical :
Fossil data :

Screen
Screen Type : Drilled Holes
Top -GL : 6.5
Bottom -GL : 7

Last Updated : 30/01/2003
Update LogonID : MattS
Last Field Check:
Printed on : 21/01/2003 03:53p.m.

MattS 30/01/2003	Borelog estimated from flushing residue - See M36/7254
suzanneg 11/06/2002	To install, both pumping and monitoring, bores to investigate the influences of groundwater abstraction effects upon artesian spring flow.



WELL M36/7254

Owner : ENVIRONMENT CANTERBURY
Street of Well : 600 CASHMERE ROAD
Locality : CASHMERE
Grid reference : M36:76456-35781 QAR 1C
Location Description :

use : Aquifer Testing

TRIM no : C06C/19422
Squalarc no :
Tideda no :

Well Type : Bore or Well
Drill Date : 05/09/2002
Well Depth : 11 Measured
Depth Drilled to :
Diameter : 62
Initial Water Depth :

Measuring Point Alt.: 12.09m +MSD Interpolated ECan DTM2003
Ground Level Alt. : same as MP
MP Description :

Driller : Unlisted
Drilling Method : Driven Pipe
Casing Material : STEEL
Pump Type :
Pump Set at : m -GL
Yield :
Drawdown :
Hours Pumped :
Specific Capacity :

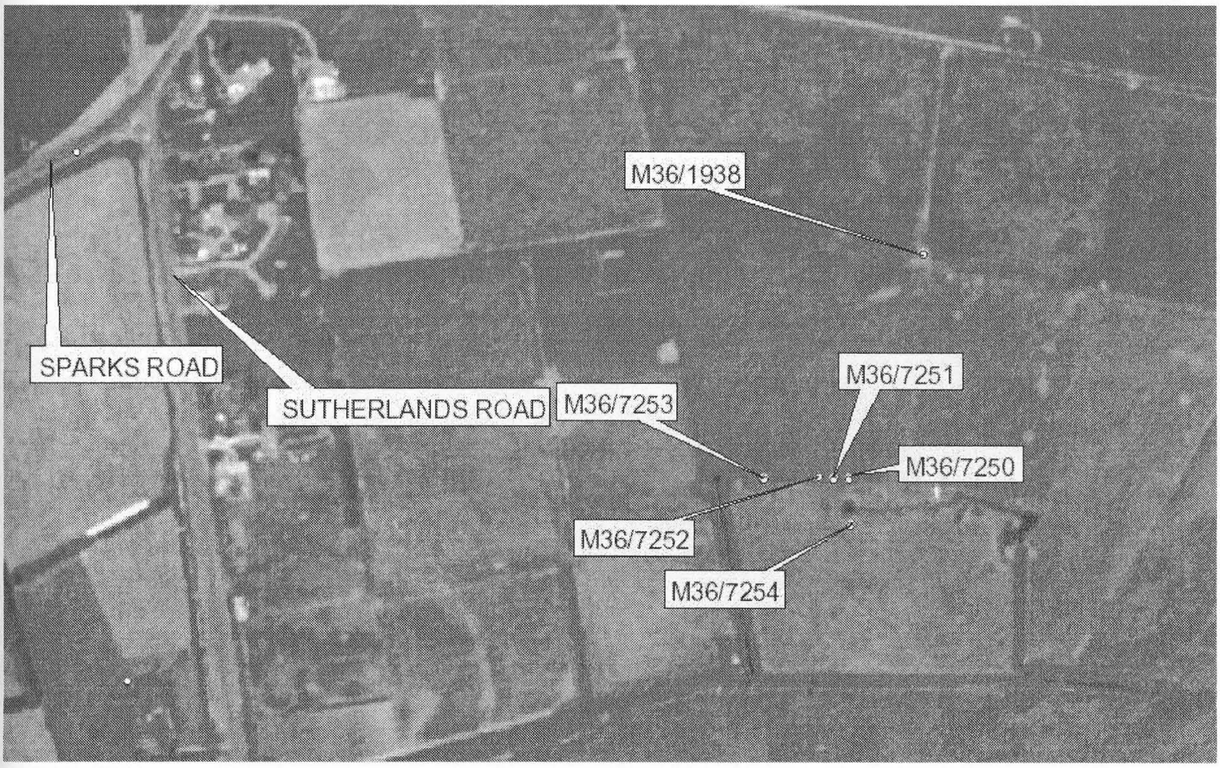
Aquifer Type :
Aquifer Name :
Aquifer Thickness : Multiple Aq :
Welldepth in Aquifer:

Reading Count : 0
Strata Logs : 7
Aquifer Test : 0
Isotope Data : 0
Geophysical :
Fossil data :

Screen
Screen Type : Drilled Holes
Top -GL : 8
Bottom -GL : 10

Last Updated : 30/01/2003
Update LogonID : MattS
Last Field Check:
Printed on : 21/01/2003 03:53p.m.

MattS 30/01/2003 — Borelog first 5m logged by hand auger.
suzanneg 11/06/2002 — To install, both pumping and monitoring, bores to investigate the influences of groundwater abstraction effects upon artesian spring flow.



Appendix F: Spring Data

SPRING M36/5796

Owner : ODELL, I & A
Street of Spring: SELWYN LAKE ROAD
Locality : BROOKSIDE
Grid reference : M36:52818-25973 QAR 5 - 15 m
Location Description : Stream bed next to bore: M36/7002

use : Stock Supply
use :
use :

TRIM no :
Squalarc no :
Tideda no :

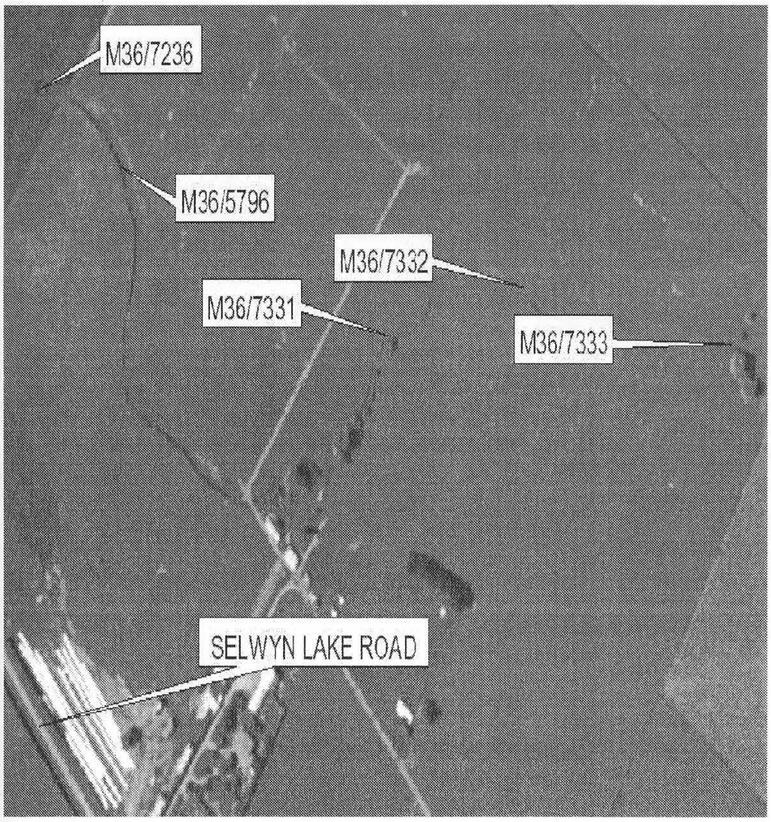
Spring Type : Artesian
Spring Character : Gravitational
Morphology : Point Source
Variability : Permanent
Geology : Gravel
Ground Level Alt. :

Aquifer Type :
Aquifer Name :

Reading Count :
Chemical data :
Isotope Data :

Last Updated : 18/08/2002
Update LogonID : MattS
Last Field Check: 24/02/1999
Data Printed on: 06/06/2003 02:40 p.m.

MattS	18/08/2002	Vents start approx 15-20m upstream of bore at mouth of culvert. Vents extend downstream approx 80m. Flow approx 35 L/s
suzannef	27/06/2001	Paddock upstream is tile drained and is thought that a large proportion of flow in the spring is determined by recharge from these. Mr Odell said that spring flows approximately 2.5 days after the Selwyn flows in this area.
Philippa	25/02/1999	Spring holes emerge from pea gravel beneath a sand layer. Observed to form vents when running. Dried up in January 1999. At least 5 major vents.



SPRING M36/7231

Owner : Triple Treasures Ltd
Street of Spring: 600 Cashmere Rd
Locality : Hoon Hay Valley
Grid reference : m36:76562-35783 QAR 5 - 15 m
Location Description : Corner of Stream D/S of m36/5934

Environment Canterbury
Your regional council

use :
use :
use :

TRIM no :
Squalarc no :
Tideda no :

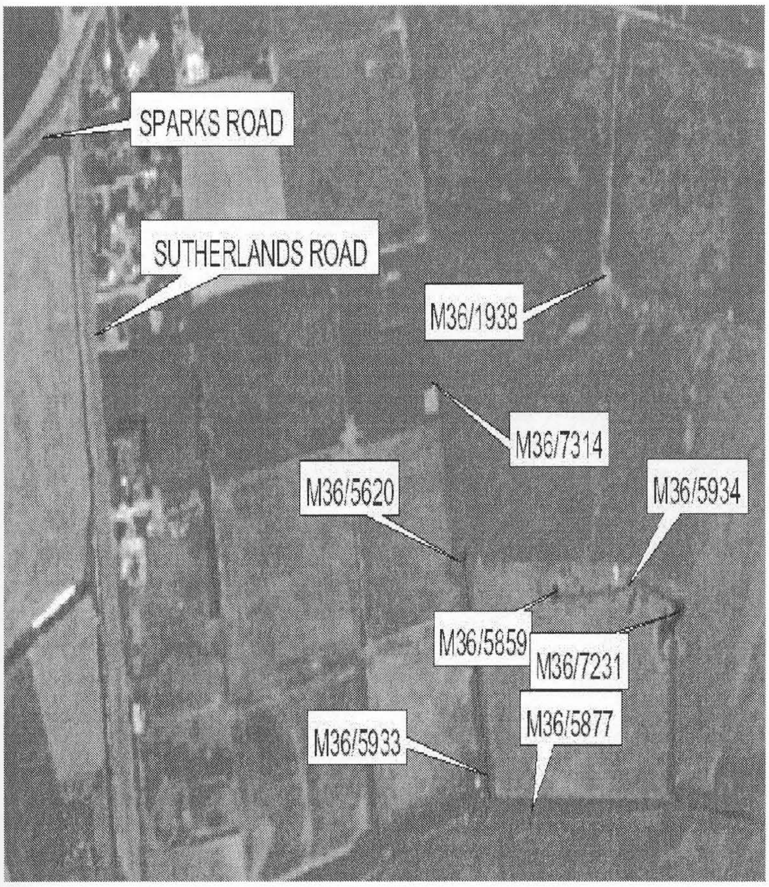
Spring Type :
Spring Character : Gravitational
Morphology : Undetermined
Variability : Permanent
Geology : Mud/Silt
Ground Level Alt. :

Aquifer Type :
Aquifer Name :

Reading Count :
Chemical data :
Isotope Data :

Last Updated : 29/01/2003
Update LogonID : MattS
Last Field Check:
Data Printed on: 06/06/2003 02:42 p.m.

MattS	29/01/2003	Gauged fow form vent est 37 l/s



SPRING M36/7332

Owner : ODELL, I & A
Street of Spring: SELWYN LAKE ROAD
Locality : BROOKSIDE
Grid reference : M36:53209-25899 QAR < 20 m
Location Description : Side of streambed Nth Side

use :
use :
use :

TRIM no :
Squalarc no :
Tideda no :

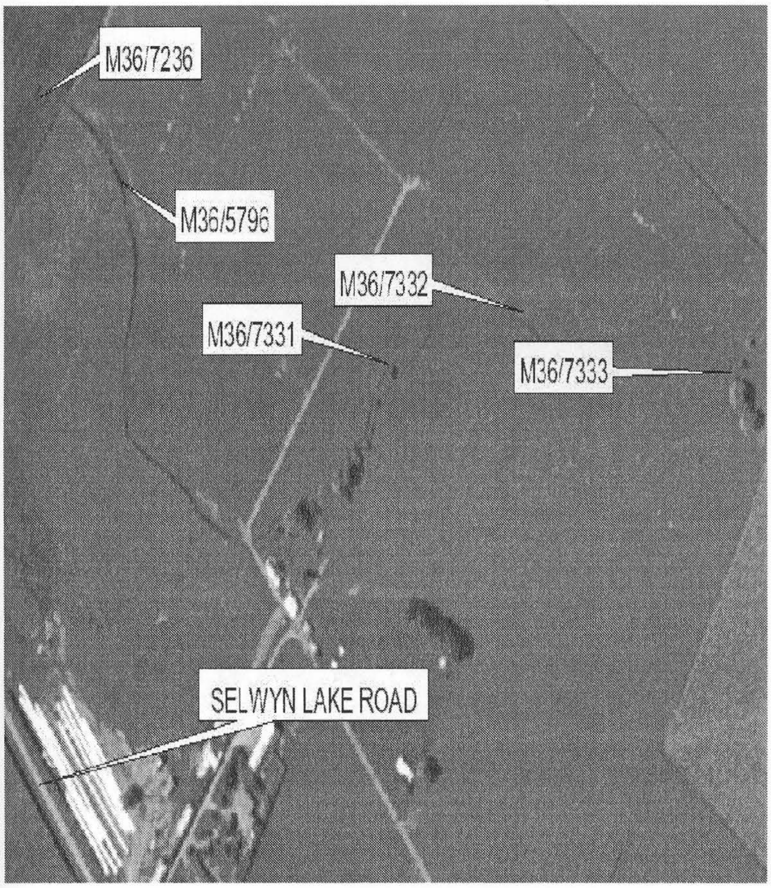
Spring Type : Artesian
Spring Character : Gravitational
Morphology : Point Source
Variability : Permanent
Geology : Gravel
Ground Level Alt. :

Aquifer Type :
Aquifer Name :

Reading Count :
Chemical data :
Isotope Data :

Last Updated : 18/08/2002
Update LogonID : MattS
Last Field Check:
Data Printed on: 06/06/2003 02:40 p.m.

MattS	18/08/2002	Signs of water inflow, soft silt bed and gas bubbles. Minimal flow.
MattS	18/08/2002	Signs of water inflow, gas bubbles & soft bed. Minimal Flow
MattS	18/08/2002	Vent flowing approx 1L/s



SPRING M36/7333

Owner : ODELL, I & A
Street of Spring: SELWYN LAKE ROAD
Locality : BROOKSIDE
Grid reference : M36:53411-25867 QAR < 20 m
Location Description : intersection of old stream bed

use :
use :
use :

TRIM no :
Squalarc no :
Tideda no :

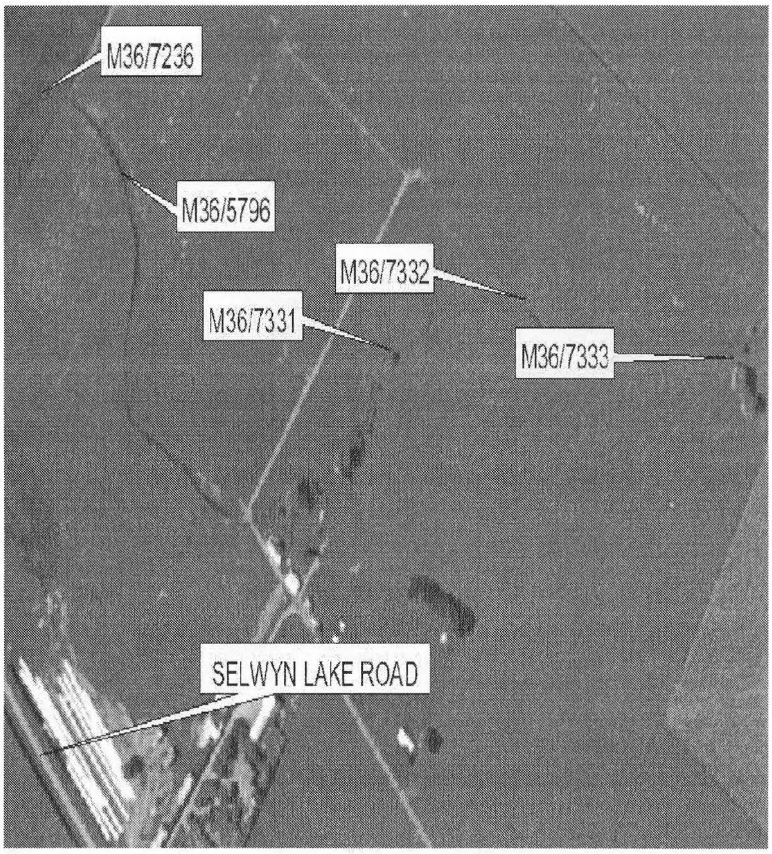
Spring Type : Artesian
Spring Character : Gravitational
Morphology : Undetermined
Variability : Undetermined
Geology : Mud/Silt
Ground Level Alt. :

Aquifer Type :
Aquifer Name :

Reading Count :
Chemical data :
Isotope Data :

Last Updated : 18/08/2002
Update LogonID : MattS
Last Field Check:
Data Printed on: 06/06/2003 02:40 p.m.

MattS	18/08/2002	Signs of water inflow, soft silt bed and gas bubbles. Minimal flow.



SPRING M36/5620

Owner :
Street of Spring: SUTHERLANDS ROAD
Locality : HALSWELL
Grid reference : M36:76375-35807 QAR 5 - 15 m
Location Description : 300m form Sutherlands Road, 150m from confluence

use :
use :
use :

TRIM no :
Squalarc no :
Tideda no :

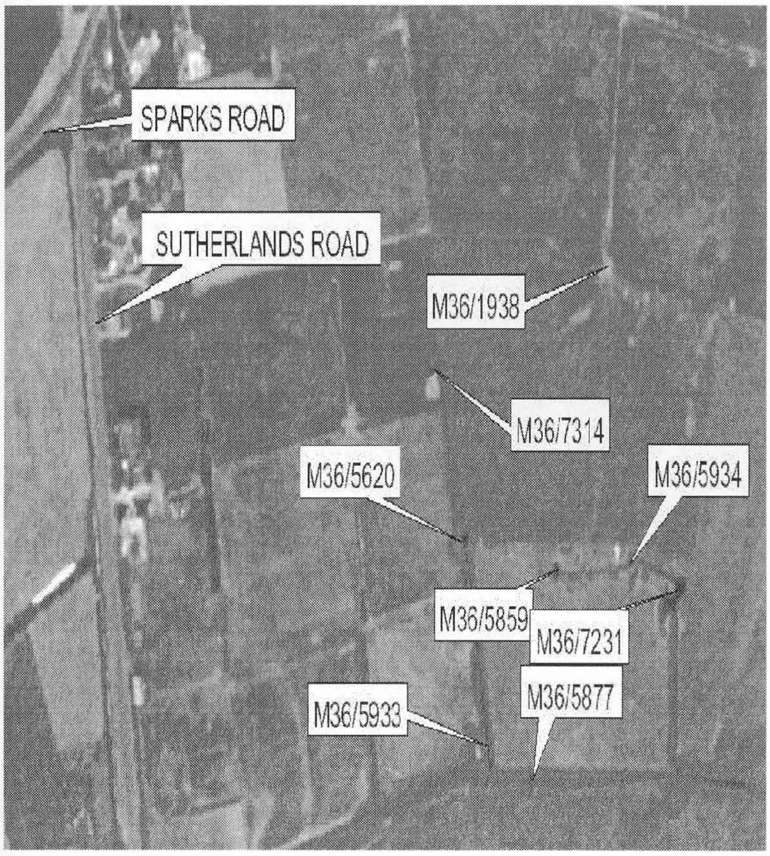
Spring Type : Artesian
Spring Character : Gravitational
Morphology : Point Source
Variability : Permanent
Geology : Mud/Silt
Ground Level Alt. :

Aquifer Type :
Aquifer Name :

Reading Count :
Chemical data :
Isotope Data :

Last Updated : 29/01/2003
Update LogonID : MattS
Last Field Check:
Data Printed on: 06/06/2003 02:41 p.m.

MattS	21/01/2003	guaged - 21l/s Est. from vent
Philippa	27/05/1999	Bubbles up from deep pool, moslty at one concentrated spot. 100 l/sec plus on 19/5/99.



SPRING M36/5859

Owner : Triple Treasures Ltd
Street of Spring: SUTHERLAND ROAD
Locality : Hoon Hay Valley
Grid reference : M36:76455-35793 QAR 5 - 15 m
Location Description : Point Source in Paddock.

Environment Canterbury
Your regional council

use : Stock Supply
use :
use :

TRIM no :
Squalarc no :
Tideda no :

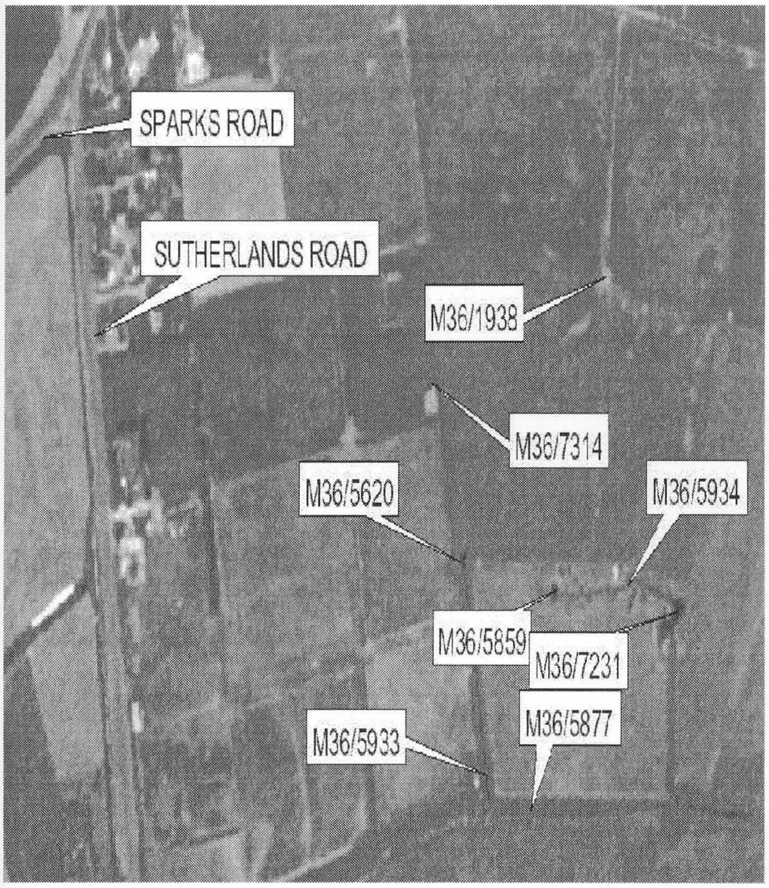
Spring Type : Artesian
Spring Character : Gravitational
Morphology : Point Source
Variability : Permanent
Geology : Sand
Ground Level Alt. :

Aquifer Type :
Aquifer Name :

Reading Count :
Chemical data :
Isotope Data :

Last Updated : 24/09/2002
Update LogonID : MattS
Last Field Check: 19/05/1999
Data Printed on: 06/06/2003 02:41 p.m.

MattS 21/09/2002 Flow 17 l/s June 2002



SPRING M36/7314

Owner :
Street of Spring: Sutherlands
Locality : Hoon Hay
Grid reference : m36:76348-35888 QAR < 20 m
Location Description : Head of drain under trees - Surface take

use : Stock Supply
use :
use :

TRIM no :
Squalarc no :
Tideda no :

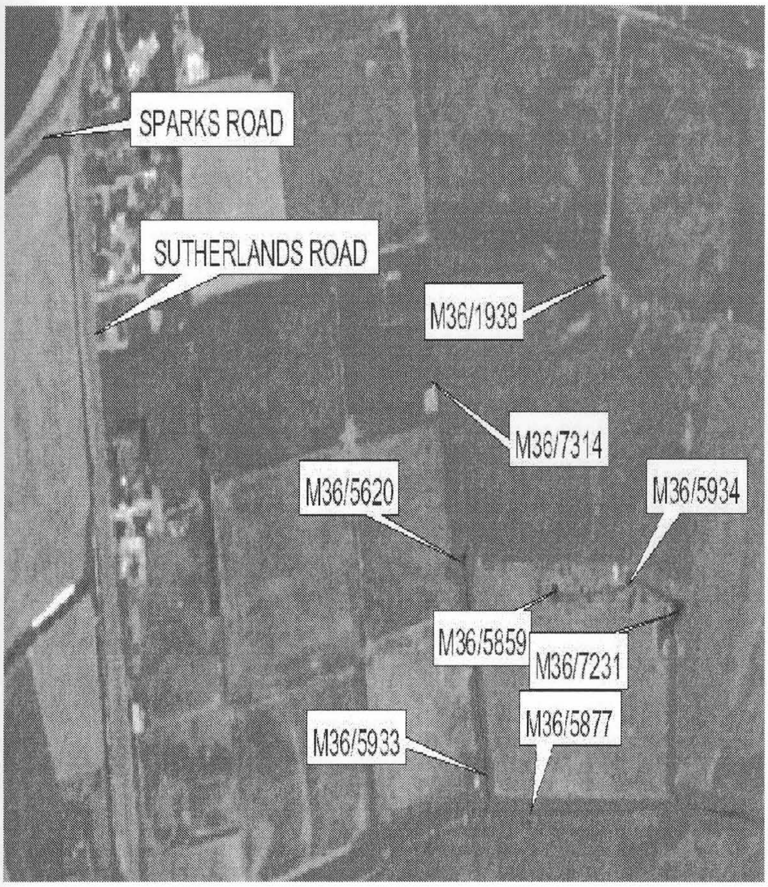
Spring Type : Artesian
Spring Character : Gravitational
Morphology : Point Source
Variability : Permanent
Geology : Mud/Silt
Ground Level Alt. :

Aquifer Type :
Aquifer Name :

Reading Count :
Chemical data :
Isotope Data :

Last Updated : 24/09/2002
Update LogonID : MattS
Last Field Check:
Data Printed on: 06/06/2003 02:42 p.m.

MattS 21/01/2003 Gauged at 4.3 L/s



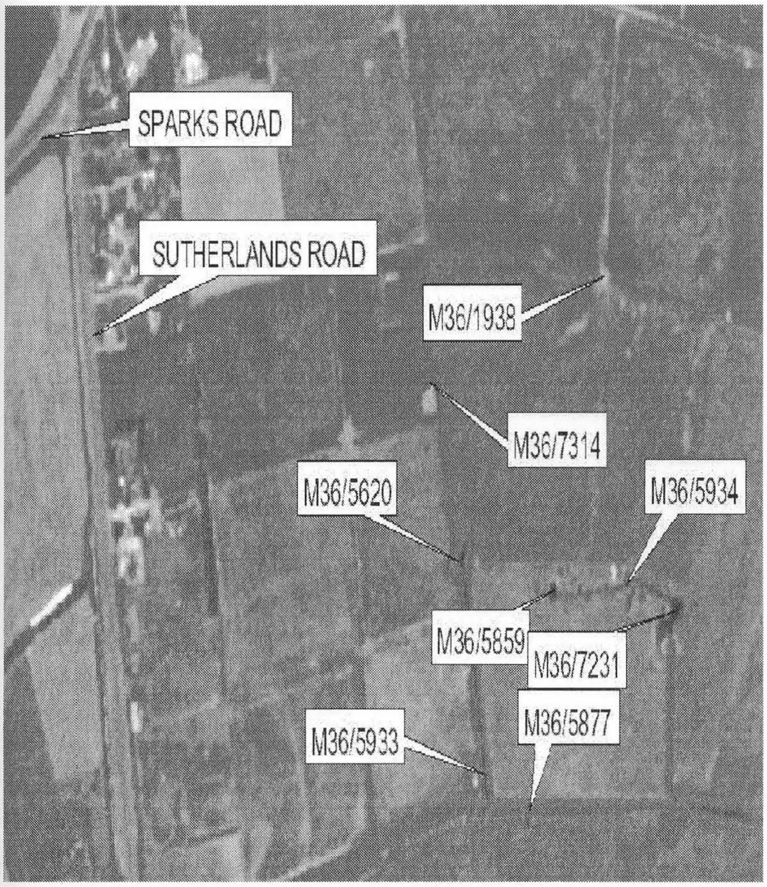
SPRING M36/5934

Owner :	Tripple Treasures Co
Street of Spring:	600 Cashmere Road
Locality :	HALSWELL
Grid reference :	M36:76518-35795 QAR 5 - 15 m
Location Description :	Pool between M36/7859 & M36/7231

use :		TRIM no :	
use :		Squalarc no :	
use :		Tideda no :	

Spring Type :	Artesian	Reading Count :	
Spring Character :	Gravitational	Chemical data :	
Morphology :	Point Source	Isotope Data :	
Variability :	Permanent		
Geology :	Mud/Silt	Last Updated :	29/01/2003
Ground Level Alt. :		Update LogonID :	MattS
		Last Field Check:	
Aquifer Type :		Data Printed on:	06/06/2003 02:42 p.m.
Aquifer Name :			

MattS 21/01/2003 Flow from vent est 30l/s - weed choked stream.



SPRING M36/5933

Owner : MORTIMER, D
Street of Spring: SUTHERLANDS ROAD
Locality : HALSWELL
Grid reference : M36:76397-35705 QAR 5 - 15 m
Location Description : approx 1m vent cone 5m u/s from cashmere stream

use :
use :
use :

TRIM no :
Squalarc no :
Tideda no :

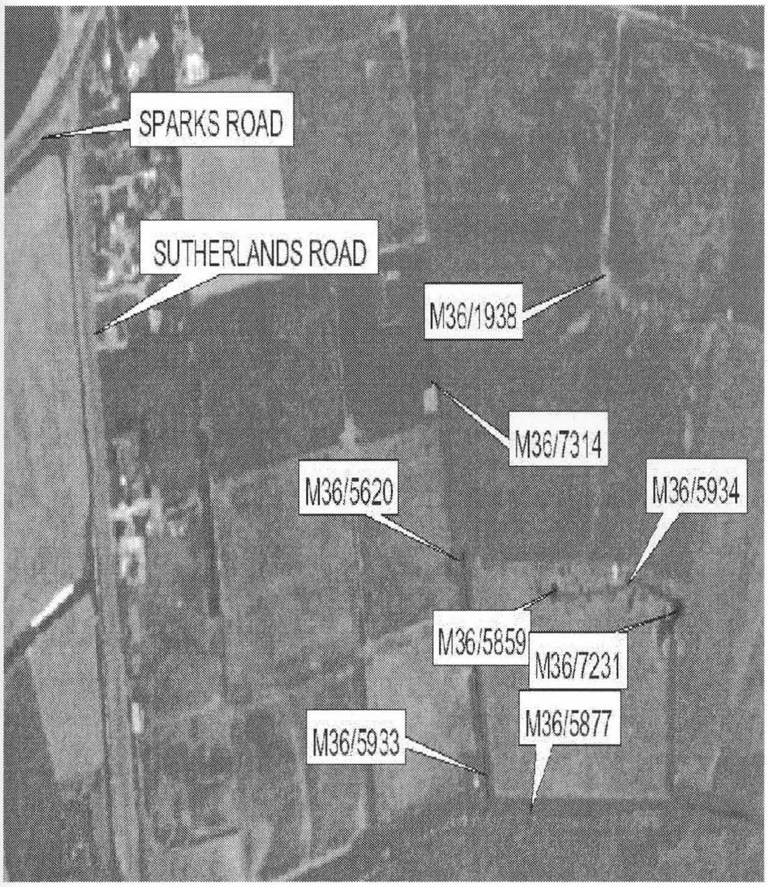
Spring Type : Artesian
Spring Character : Gravitational
Morphology : Point Source
Variability : Permanent
Geology : Mud/Silt
Ground Level Alt. :

Aquifer Type :
Aquifer Name :

Reading Count :
Chemical data :
Isotope Data :

Last Updated : 29/01/2003
Update LogonID : matts
Last Field Check:
Data Printed on: 06/06/2003 02:42 p.m.

MattS 21/01/2003 Gauged flow from vent 29 l/s



SPRING M36/5877

Owner : MORTIMER, D
Street of Spring: SUTHERLANDS ROAD
Locality : HALWELL
Grid reference : M36:76434-35690 QAR 5 - 15 m
Location Description : 3x4m pit next to poplar beside Cashmere stream

use :
use :
use :

TRIM no :
Squalarc no :
Tideda no :

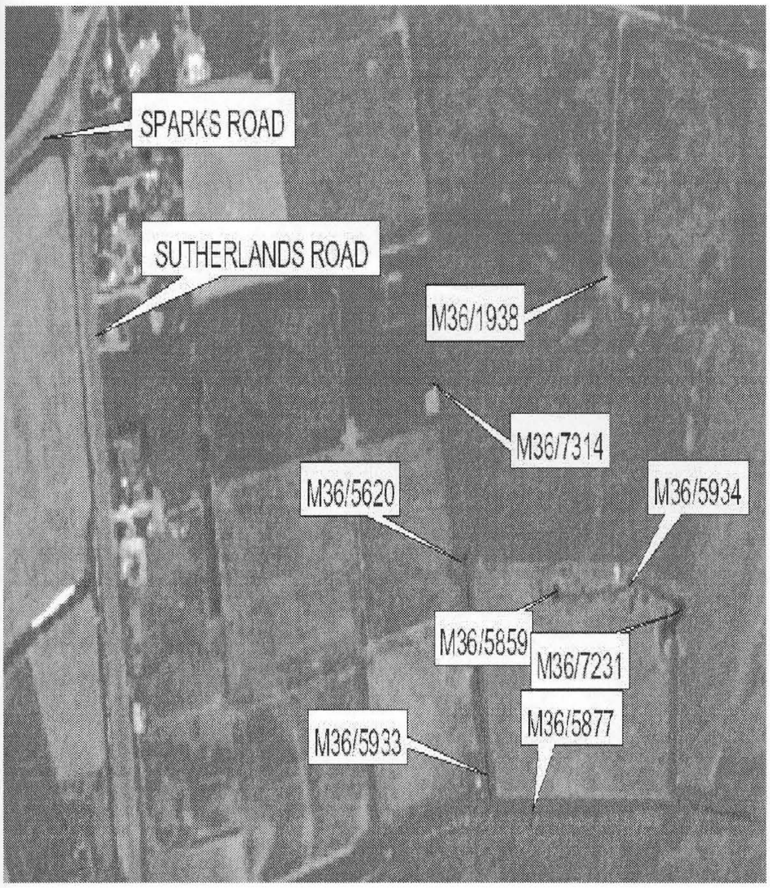
Spring Type : Artesian
Spring Character : Gravitational
Morphology : Point Source
Variability : Permanent
Geology : Mud/Silt
Ground Level Alt. :

Aquifer Type :
Aquifer Name :

Reading Count :
Chemical data :
Isotope Data :

Last Updated : 29/01/2003
Update LogonID : matts
Last Field Check:
Data Printed on: 06/06/2003 02:41 p.m.

MattS 21/01/2003 Gauged flow from vent 25 l/s



SPRING M36/7331

Owner : ODELL, I & A
Street of Spring: SELWYN LAKE ROAD
Locality : BROOKSIDE
Grid reference : M36:53077-25869 QAR < 20 m
Location Description : Large vent on west bank

use :
use :
use :

TRIM no :
Squalarc no :
Tideda no :

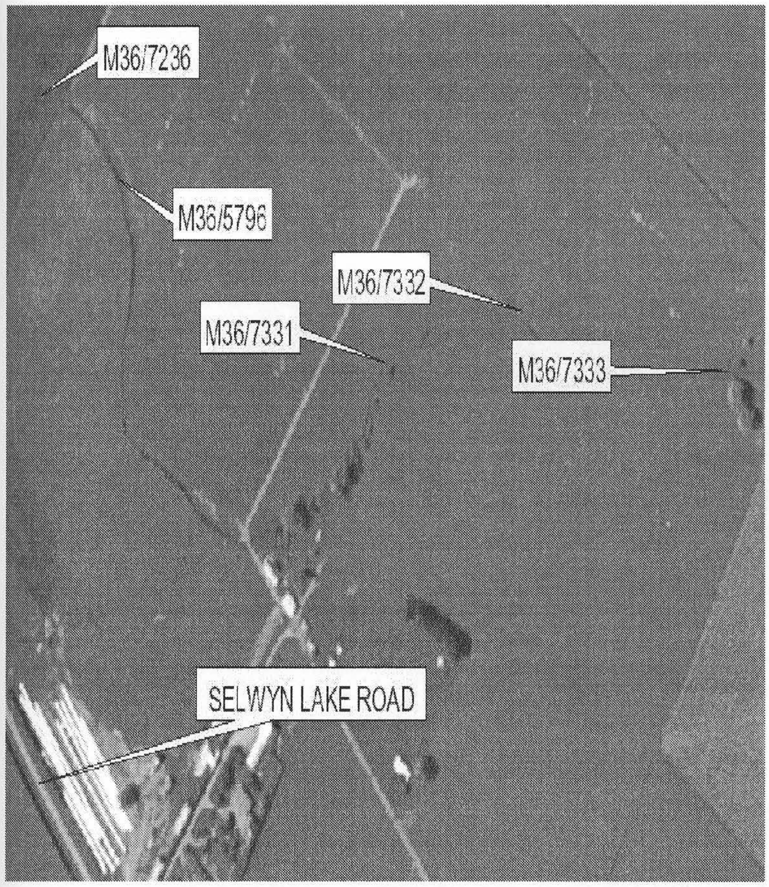
Spring Type : Artesian
Spring Character : Gravitational
Morphology : Point Source
Variability : Permanent
Geology : Gravel
Ground Level Alt. :

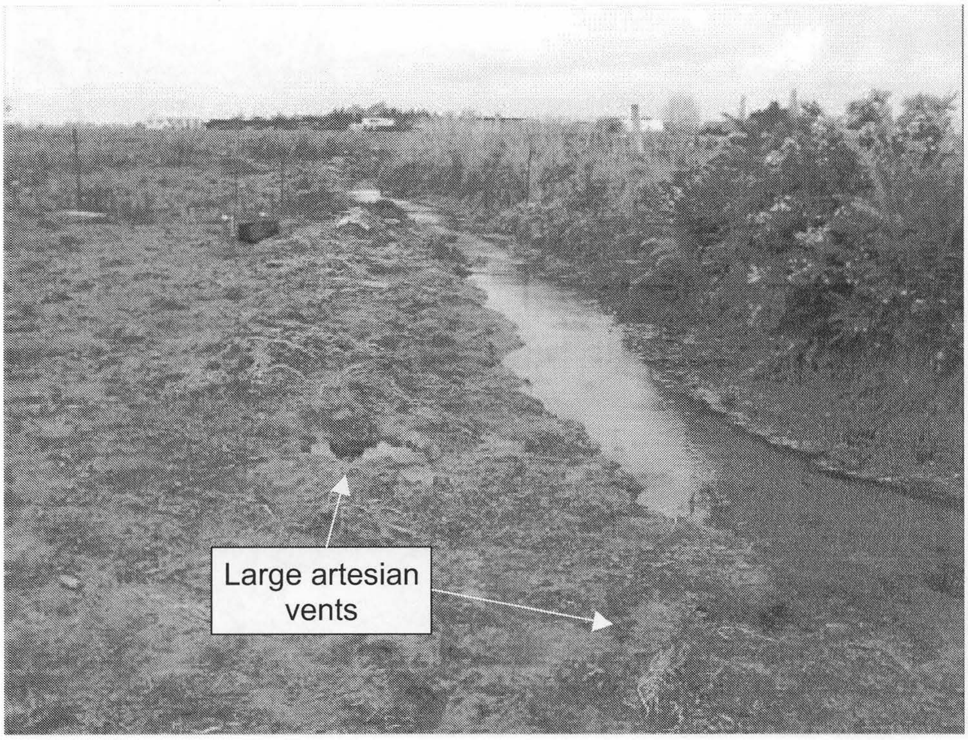
Aquifer Type :
Aquifer Name :

Reading Count :
Chemical data :
Isotope Data :

Last Updated : 18/08/2002
Update LogonID : MattS
Last Field Check:
Data Printed on: 06/06/2003 02:40 p.m.

MattS 18/08/2002 Approx Flow 8L/s

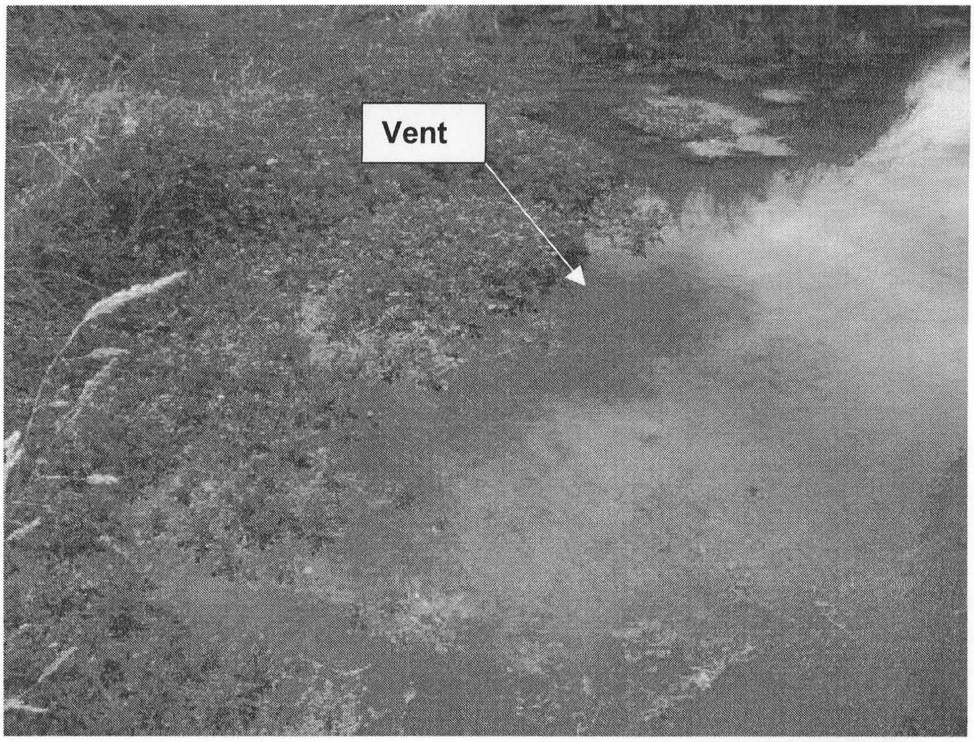




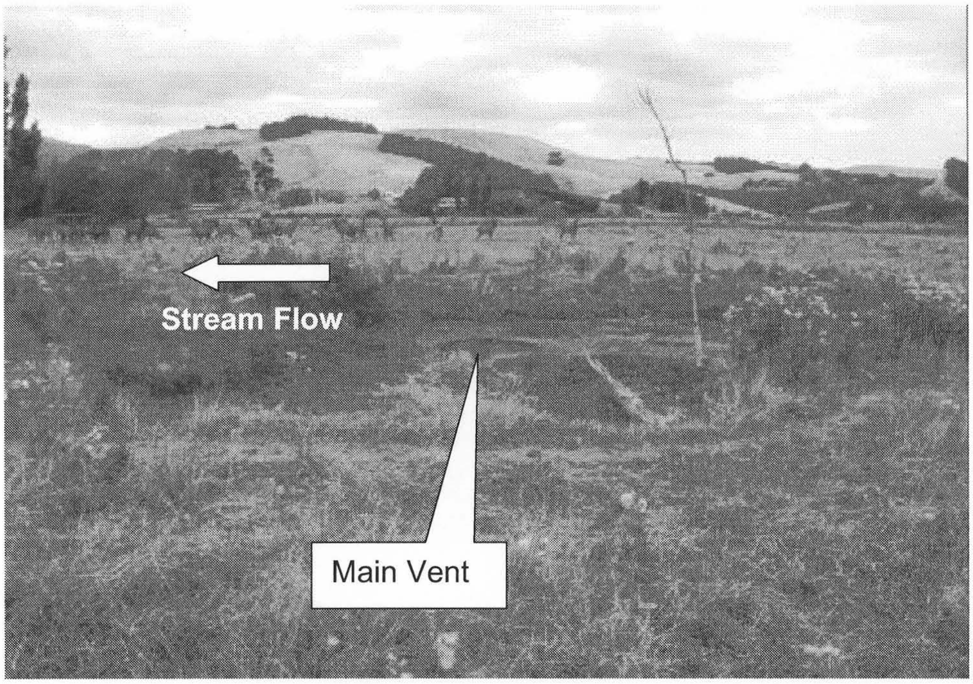
Spring area M36/5796, large vents on bank and smaller vents in stream.

Close up of larger vent discharging to stream.

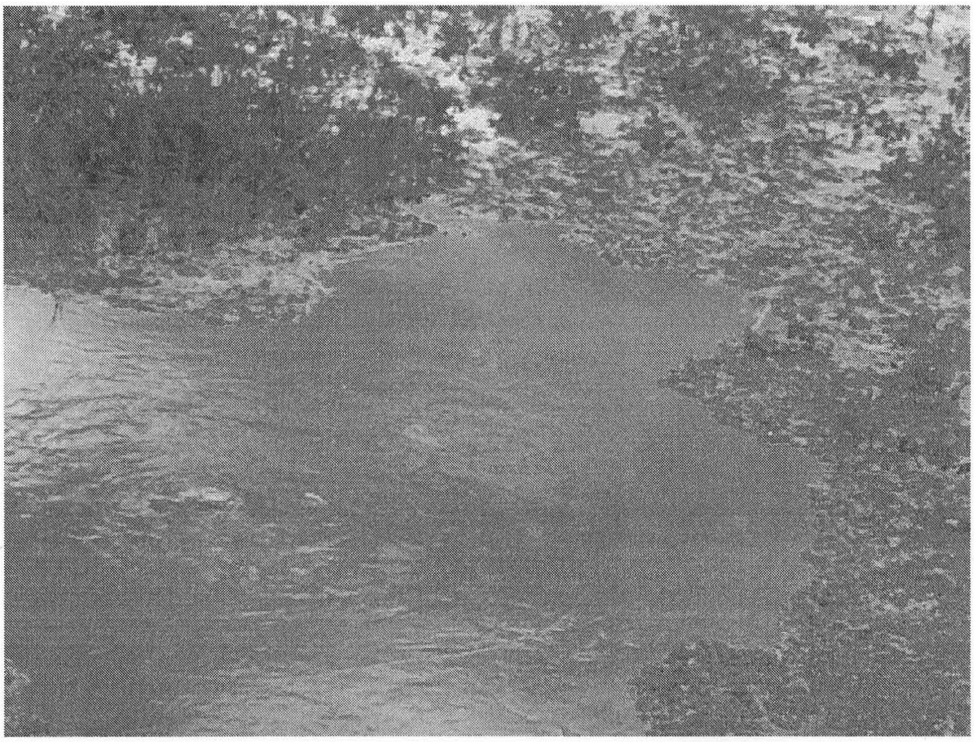
Spring M36/5620 looking SW



Close up of M36/5620 vent structure.

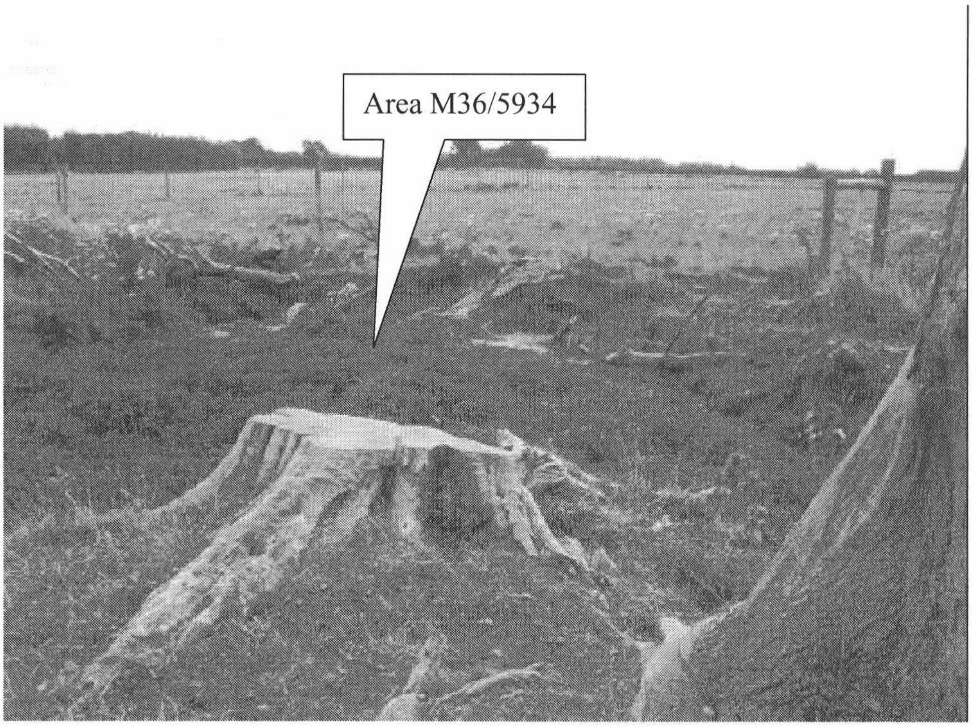


Study spring M36/5859



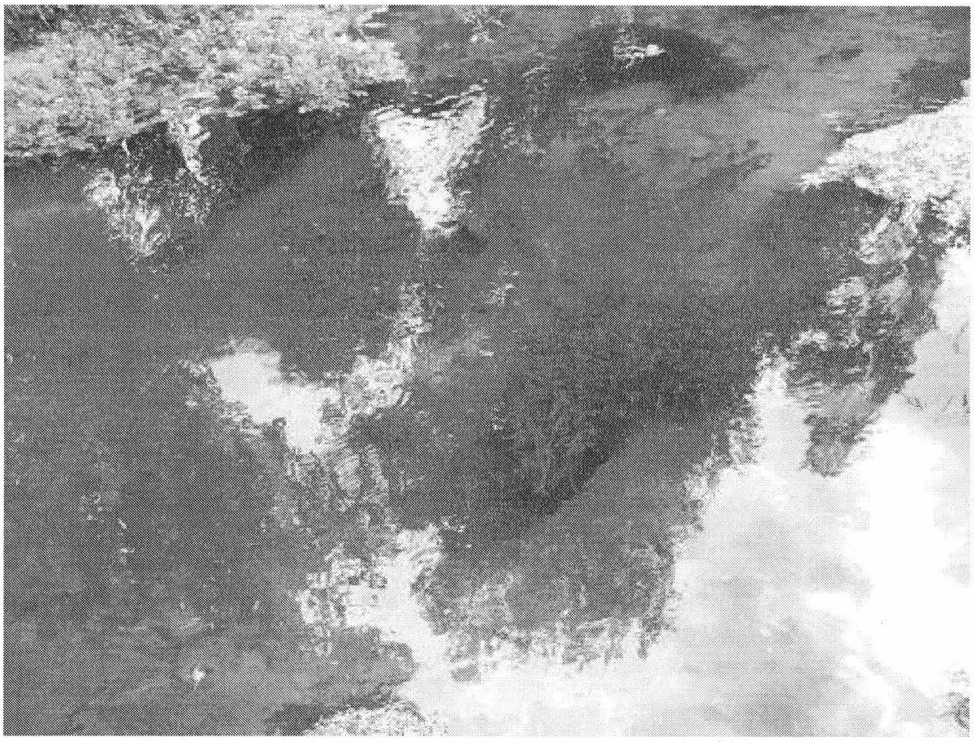
Close up of M36/5859 main vent discharging at around 17 L/s

M36/5877 taken from in Sutherlands Drain, looking N.

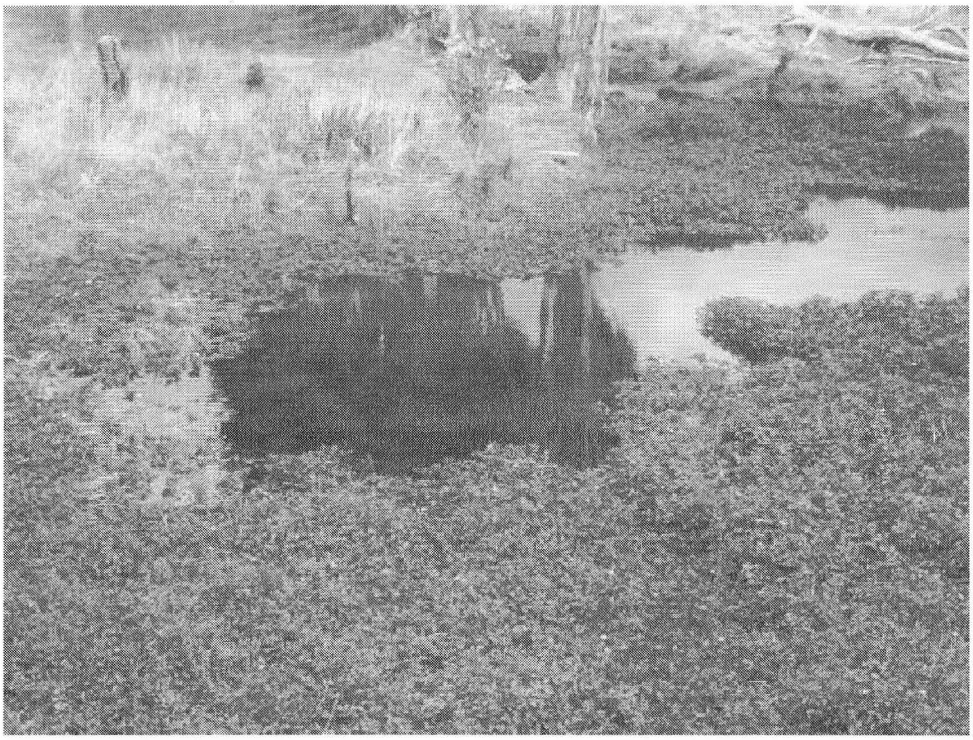


Spring area M36/5934, note vegetation choked stream.

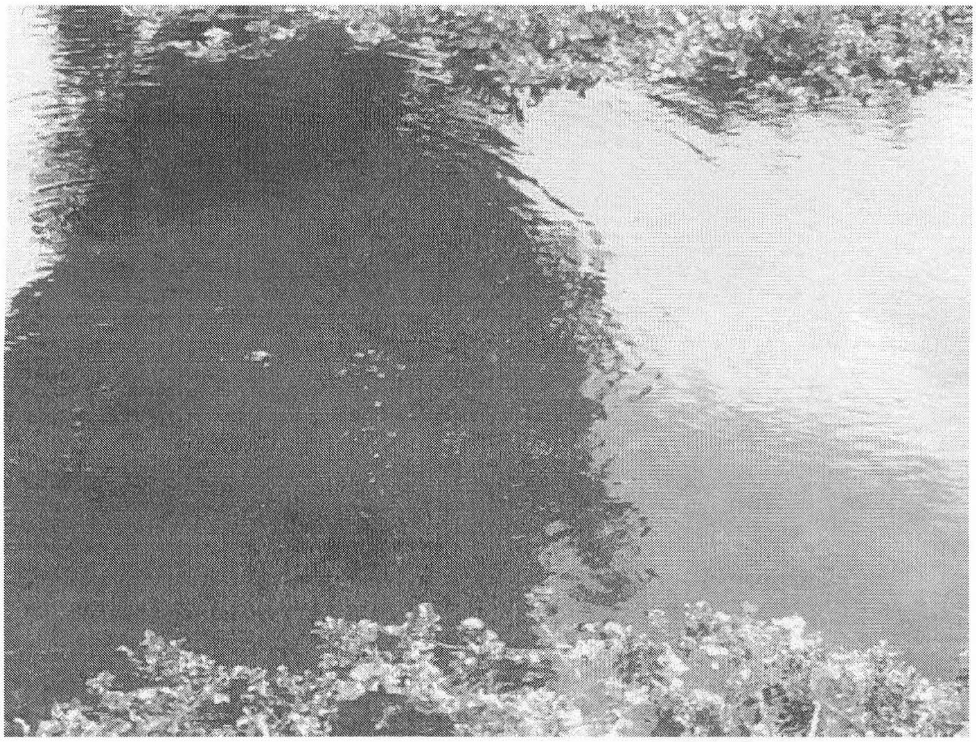
M36/5933 looking N toward M36/5620



Close up of M36/5933 vent structure.



M36/7331 looking S.



Close up of M36/7331 showing gas effervescing from a vent fissure.

M36/7314, consisting of a deep pool with comparatively low flow.

Appendix G: Gauging Data

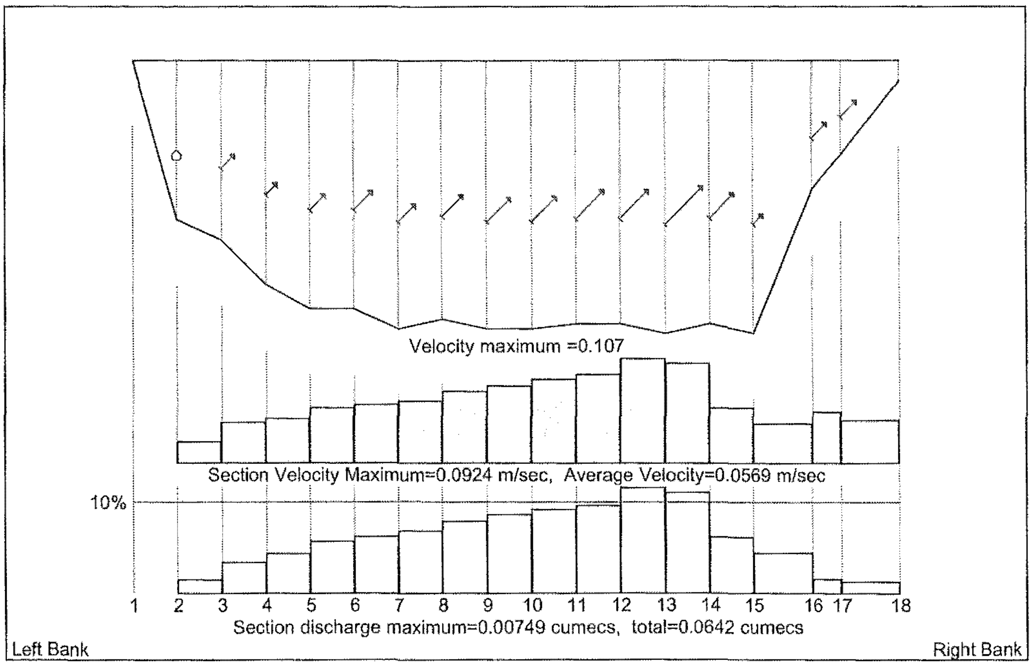
Gauging Report

Site No	: 1
River at	: Odell 1
Party	: N & M
Map Ref	: M36:
Date	: 12/2/2002
Start time	: 13:00
End time	: 13:40
Method	: Wading
Total Discharge	: 0.06422 cumecs
Total Area	: 1.129 square metres
Maximum Depth	: 0.55 metres
Mean Velocity	: 0.05687 m/sec
Surface Width	: 2.6 metres
Wetted Perimeter	: 3.078 metres
Hydraulic Radius	: 0.3668 metres
Verticals	: 18

Dist	Depth		Corr	M	Rev	Time	Vel	MeanVel	Area	Discharge
Left Bank										
1.3	0				--- Waters Edge --					
1.45	0.32	.6	1	1	0	40	0	0	0.024	0
1.6	0.36	.6	1	1	14	40.8	0.039	0.039	0.051	0.001
1.75	0.45	.6	1	1	12	44	0.034	0.034	0.0607	0.0022
1.9	0.5	.6	1	1	18	41.1	0.045	0.045	0.0712	0.0028
2.05	0.5	.6	1	1	24	41.6	0.053	0.053	0.075	0.0037
2.2	0.54	.6	1	1	21	40.1	0.05	0.05	0.078	0.004
2.35	0.52	.6	1	1	31	45	0.06	0.06	0.0795	0.0044
2.5	0.54	.6	1	1	33	41.4	0.067	0.067	0.0795	0.0051
2.65	0.54	.6	1	1	34	40.6	0.07	0.07	0.081	0.0055
2.8	0.53	.6	1	1	39	40.1	0.078	0.078	0.0802	0.0059
2.95	0.53	.6	1	1	39	40.1	0.078	0.078	0.0795	0.0062
3.1	0.55	.6	1	1	57	40.1	0.107	0.107	0.081	0.0075
3.25	0.53	.6	1	1	34	40.7	0.07	0.07	0.081	0.0071
3.4	0.55	.6	1	1	8	45.1	0.028	0.028	0.081	0.004
3.6	0.26	.6	1	1	19	46.3	0.043	0.043	0.081	0.0029
3.7	0.19	.6	1	1	20	41.4	0.047	0.047	0.0225	0.001
3.9	0.04				---Effective Waters Edge 80% --				0.023	
Right Bank										

Meter : 1
Serial Number : c2-168825

Slope	Offset	Max
0.063	0.017	


Velocity maximum =0.107
Section Velocity Maximum=0.0924 m/sec, Average Velocity=0.0569 m/sec
10%
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Section discharge maximum=0.00749 cumecs, total=0.0642 cumecs
Left Bank
Right Bank

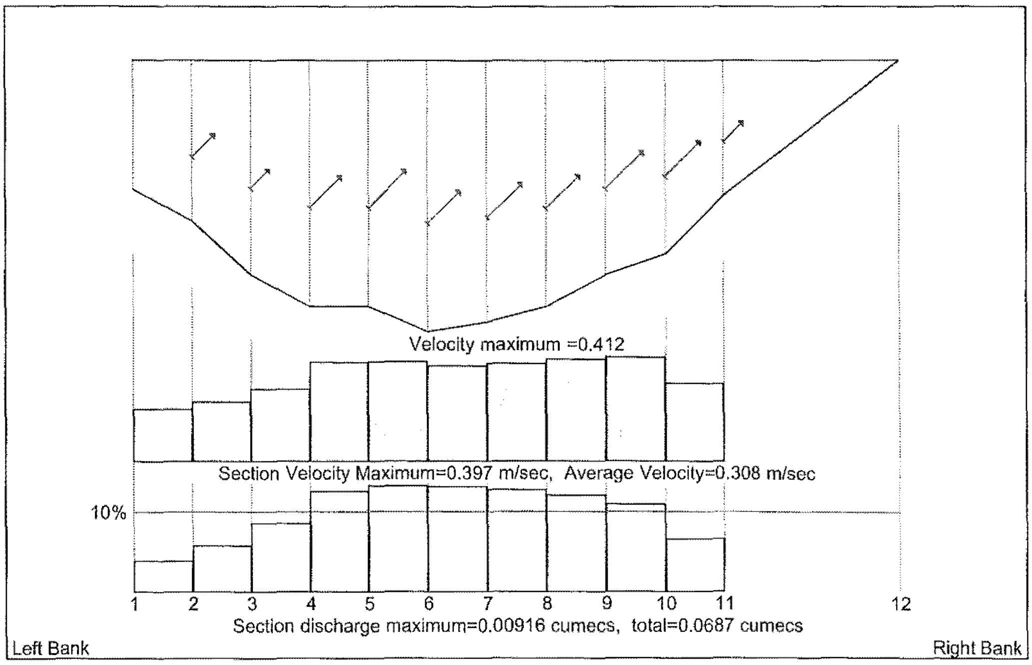
Gauging Report

Site No	: 2
River at	: Odell 2
Party	: M & N
Map Ref	: M36:
Date	: 12/2/2002
Start time	: 13:40
End time	: 14:00
Method	: Wading
Turbidity	: 1
Total Discharge	: 0.06871 cumecs
Total Area	: 0.2229 square metres
Maximum Depth	: 0.254 metres
Mean Velocity	: 0.3082 m/sec
Surface Width	: 1.3 metres
Wetted Perimeter	: 1.37 metres
Hydraulic Radius	: 0.1626 metres
Verticals	: 12

Dist	Depth	Corr	M	Rev	Time	Vel	MeanVel	Area	Discharge
Left Bank									
1.2	0.12			---Effective Waters Edge 80% --					
1.3	0.15	.6 1	3	38	40.5	0.249	0.249	0.0135	0.0027
1.4	0.2	.6 1	3	31	40.3	0.206	0.206	0.0175	0.004
1.5	0.23	.6 1	3	53	40.6	0.343	0.343	0.0215	0.0059
1.6	0.23	.6 1	3	63	40.4	0.409	0.409	0.023	0.0087
1.7	0.254	.6 1	3	54	40.8	0.348	0.348	0.0242	0.0092
1.8	0.245	.6 1	3	58	40.3	0.378	0.378	0.025	0.0091
1.9	0.23	.6 1	3	56	40.4	0.364	0.364	0.0237	0.0088
2	0.2	.6 1	3	63	40.1	0.412	0.412	0.0215	0.0083
2.1	0.18	.6 1	3	59	40.5	0.382	0.382	0.019	0.0075
2.2	0.125	.6 1	3	33	40.7	0.216	0.216	0.0153	0.0046
2.5	0			--- Waters Edge --				0.0187	
Right Bank									

Meter : 3
Serial Number : 3-168726

Slope	Offset	Max
0.257	0.008	


Velocity maximum =0.412
Section Velocity Maximum=0.397 m/sec, Average Velocity=0.308 m/sec
10%
1 2 3 4 5 6 7 8 9 10 11 12
Section discharge maximum=0.00916 cumecs, total=0.0687 cumecs
Left Bank
Right Bank

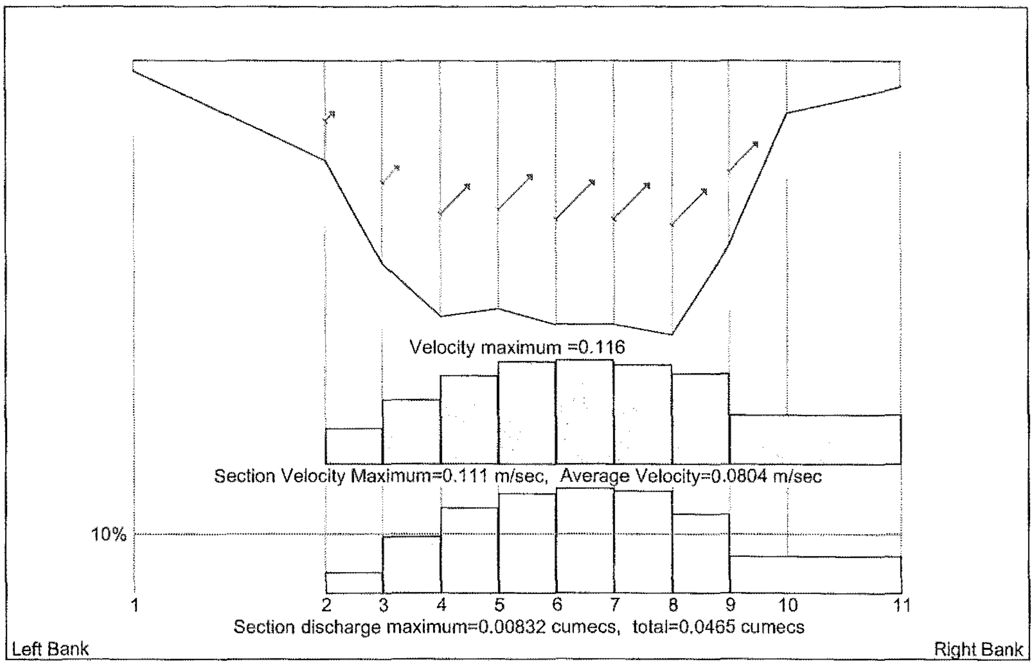
Gauging Report

Site No	: 3
River at	: Odell Spring
Party	: M&N
Map Ref	: 36
Date	: 12/2/2002
Start time	: 12:00
End time	: 13:00
Method	: Wading
Total Discharge	: 0.04647 cumecs
Total Area	: 0.5782 square metres
Maximum Depth	: 0.52 metres
Mean Velocity	: 0.08037 m/sec
Surface Width	: 2 metres
Wetted Perimeter	: 2.382 metres
Hydraulic Radius	: 0.2428 metres
Verticals	: 11

Dist	Depth		Corr	M	Rev	Time	Vel	MeanVel	Area	Discharge
Left Bank										
1.3	0.02				--- Waters Edge --					
1.8	0.19	.6	1	1	7	40.9	0.028	0.028	0.0525	0
1.95	0.385	.6	1	1	21	40.3	0.05	0.05	0.0431	0.0017
2.1	0.485	.6	1	1	45	40.5	0.087	0.087	0.0653	0.0045
2.25	0.47	.6	1	1	54	40.2	0.102	0.102	0.0716	0.0068
2.4	0.5	.6	1	1	64	40.7	0.116	0.116	0.0727	0.0079
2.55	0.5	.6	1	1	57	40.4	0.106	0.106	0.075	0.0083
2.7	0.52	.6	1	1	56	40	0.105	0.105	0.0765	0.0081
2.85	0.35	.6	1	1	45	40	0.088	0.088	0.0652	0.0063
3	0.1				--- Sounding --				0.0337	
3.3	0.05				---Effective Waters Edge 60% --				0.0225	
Right Bank										

Meter : 1
Serial Number : 1-165323

Slope	Offset	Max
0.063	0.017	


Velocity maximum =0.116
Section Velocity Maximum=0.111 m/sec, Average Velocity=0.0804 m/sec
10%
1
2
3
4
5
6
7
8
9
10
11
Section discharge maximum=0.00832 cumecs, total=0.0465 cumecs
Left Bank
Right Bank

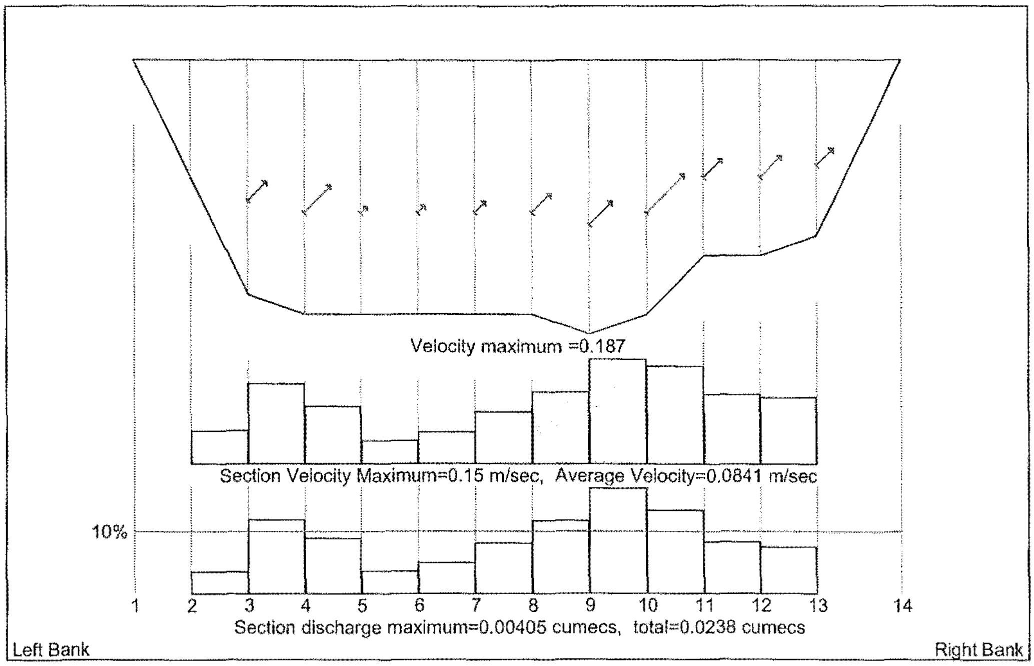
Gauging Report

Site No	: M36/5620
River at	: Cashmere Strm
Party	: Matt
Date	: 1/11/2002
Start time	: 16:30
End time	: 16:50
Total Discharge	: 0.02376 cumecs
Total Area	: 0.2825 square metres
Maximum Depth	: 0.14 metres
Mean Velocity	: 0.0841 m/sec
Surface Width	: 2.7 metres
Wetted Perimeter	: 2.734 metres
Hydraulic Radius	: 0.1033 metres
Verticals	: 14

Dist	Depth		Corr	M	Rev	Time	Vel	MeanVel	Area	Discharge
Left Bank										
1.2	0				--- Waters Edge --					
1.4	0.06	.2	1	1	0	0	0	0	0.006	0
1.6	0.12	.6	1	1	50	40.2	0.095	0.095	0.018	0.0009
1.8	0.13	.6	1	1	75	40.6	0.133	0.133	0.025	0.0029
2	0.13	.6	1	1	9	40.4	0.031	0.031	0.026	0.0021
2.2	0.13	.6	1	1	13	40.4	0.037	0.037	0.026	0.0009
2.4	0.13	.6	1	1	25	41.6	0.055	0.055	0.026	0.0012
2.6	0.13	.6	1	1	49	40.1	0.094	0.094	0.026	0.0019
2.8	0.14	.6	1	1	61	40.1	0.113	0.113	0.027	0.0028
3	0.13	.6	1	1	109	40.3	0.187	0.187	0.027	0.0041
3.2	0.1	.6	1	1	49	40.7	0.093	0.093	0.023	0.0032
3.4	0.1	.6	1	1	58	40.5	0.107	0.107	0.02	0.002
3.6	0.09	.6	1	1	43	40.6	0.084	0.084	0.019	0.0018
3.9	0				--- Waters Edge --				0.0135	
Right Bank										

Meter : 1
Serial Number : 1-165323

Slope	Offset	Max
0.063	0.017	


Velocity maximum =0.187
Section Velocity Maximum=0.15 m/sec, Average Velocity=0.0841 m/sec
10%
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Section discharge maximum=0.00405 cumecs, total=0.0238 cumecs
Left Bank
Right Bank

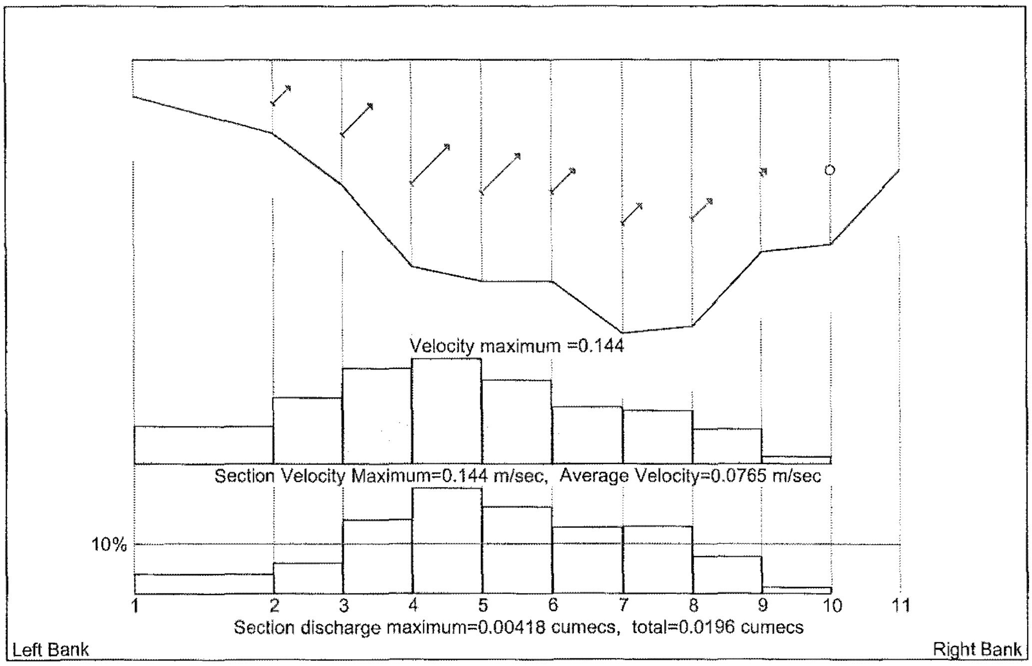
Gauging Report

Site No	: M36/5859
River at	: Cashmere Strm
Party	: Matt
Date	: 1/11/2002
Start time	: 14:00
End time	: 14:20
Total Discharge	: 0.01962 cumecs
Total Area	: 0.2565 square metres
Maximum Depth	: 0.37 metres
Mean Velocity	: 0.07648 m/sec
Surface Width	: 1.1 metres
Wetted Perimeter	: 1.285 metres
Hydraulic Radius	: 0.1996 metres
Verticals	: 11

Dist	Depth	Corr	M		Rev	Time	Vel	MeanVel	Area	Discharge
Left Bank										
1.2	0.05				---Effective Waters Edge 80% --					
1.4	0.1	.6	1	1	31	40.7	0.065	0.065	0.015	0.0008
1.5	0.17	.6	1	1	64	40.5	0.117	0.117	0.0135	0.0012
1.6	0.28	.6	1	1	81	40.1	0.144	0.144	0.0225	0.0029
1.7	0.3	.6	1	1	81	40.2	0.144	0.144	0.029	0.0042
1.8	0.3	.6	1	1	44	40.6	0.085	0.085	0.03	0.0034
1.9	0.37	.6	1	1	35	40.2	0.072	0.072	0.0335	0.0026
2	0.36	.6	1	1	37	40.5	0.075	0.075	0.0365	0.0027
2.1	0.26	.6	1	1	3	44	0.021	0.021	0.031	0.0015
2.2	0.25	.6	1	1	0	40	0	0	0.0255	0.0003
2.3	0.15				--- Waters Edge --				0.02	
Right Bank										

Meter : 1
Serial Number : 1-165323

Slope	Offset	Max
0.063	0.017	


Velocity maximum =0.144
Section Velocity Maximum=0.144 m/sec, Average Velocity=0.0765 m/sec
10%
1
2
3
4
5
6
7
8
9
10
11
Section discharge maximum=0.00418 cumecs, total=0.0196 cumecs
Left Bank
Right Bank

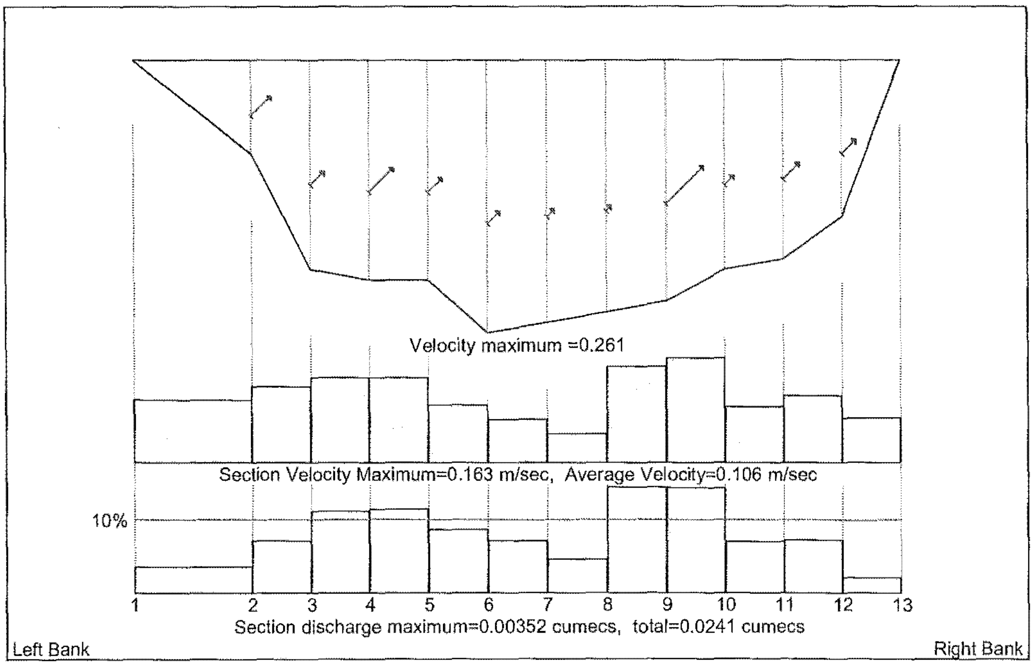
Gauging Report

Site No	: M36/5877
River at	: Cashmere Strm
Party	: Matt
Date	: 1/11/2002
Start time	: 15:30
End time	: 15:50
Total Discharge	: 0.02412 cumecs
Total Area	: 0.2275 square metres
Maximum Depth	: 0.26 metres
Mean Velocity	: 0.106 m/sec
Surface Width	: 1.3 metres
Wetted Perimeter	: 1.475 metres
Hydraulic Radius	: 0.1543 metres
Verticals	: 13

Dist	Depth		Corr	M	Rev	Time	Vel	MeanVel	Area	Discharge
Left Bank										
1	0				---Effective Waters Edge 70% --					
1.2	0.09	.6	1	1	79	40.3	0.14	0.14	0.009	0.0009
1.3	0.2	.6	1	1	51	40.1	0.097	0.097	0.0145	0.0017
1.4	0.21	.6	1	1	96	40.1	0.168	0.168	0.0205	0.0027
1.5	0.21	.6	1	1	52	40.6	0.098	0.098	0.021	0.0028
1.6	0.26	.6	1	1	42	40.4	0.082	0.082	0.0235	0.0021
1.7	0.25	.6	1	1	24	41.5	0.053	0.053	0.0255	0.0017
1.8	0.24	.6	1	1	14	40.7	0.039	0.039	0.0245	0.0011
1.9	0.23	.6	1	1	155	40	0.261	0.261	0.0235	0.0035
2	0.2	.6	1	1	31	41	0.065	0.065	0.0215	0.0035
2.1	0.19	.6	1	1	60	40.4	0.111	0.111	0.0195	0.0017
2.2	0.15	.6	1	1	52	40	0.099	0.099	0.017	0.0018
2.3	0				---Effective Waters Edge 70% --				0.0075	0.0005
Right Bank										

Meter : 1
Serial Number : 1-165323

Slope	Offset	Max
0.063	0.017	


Velocity maximum =0.261
Section Velocity Maximum=0.163 m/sec, Average Velocity=0.106 m/sec
10%
1
2
3
4
5
6
7
8
9
10
11
12
13
Section discharge maximum=0.00352 cumecs, total=0.0241 cumecs
Left Bank
Right Bank

Gauging Report

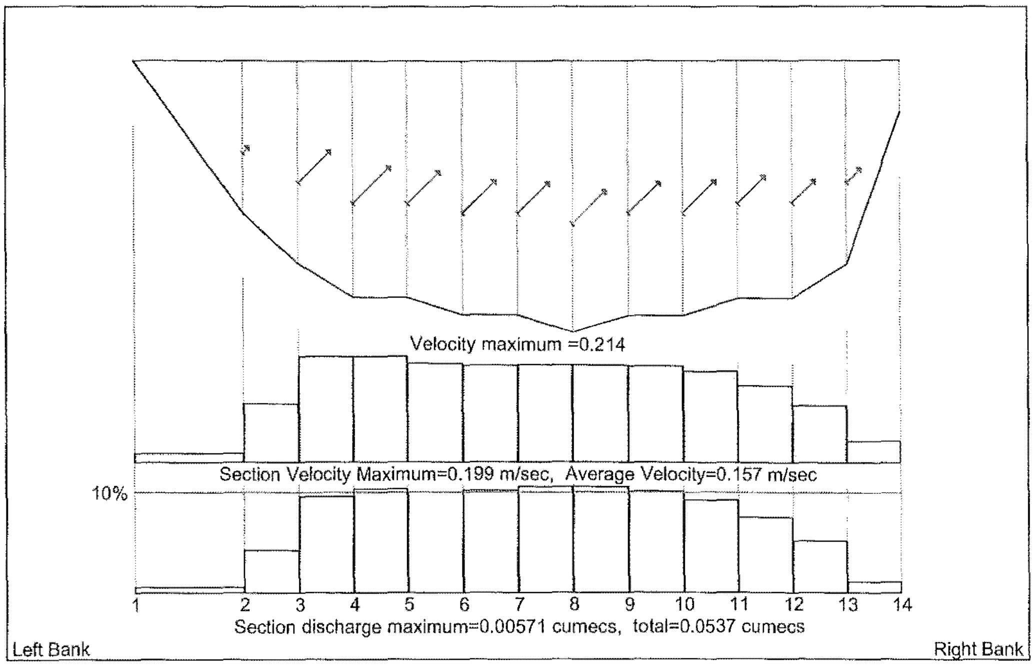
Site No	: M36/5933
River at	: Cashmere Strm
Party	: Matt
Date	: 1/11/2002
Start time	: 16:00
End time	: 16:20
Total Discharge	: 0.05373 cumecs
Total Area	: 0.342 square metres
Maximum Depth	: 0.16 metres
Mean Velocity	: 0.1571 m/sec
Surface Width	: 2.8 metres
Wetted Perimeter	: 2.835 metres
Hydraulic Radius	: 0.1207 metres
Verticals	: 14

Dist	Depth		Corr	M	Rev	Time	Vel	MeanVel	Area	Discharge
Left Bank										
1.2	0				---Effective Waters Edge 50% --					
1.6	0.09	.6	1	1	15	45.7	0.038	0.038	0.018	0.0003
1.8	0.12	.6	1	1	106	40	0.184	0.184	0.021	0.0023
2	0.14	.6	1	1	125	40	0.214	0.214	0.026	0.0052
2.2	0.14	.6	1	1	107	40.2	0.185	0.185	0.028	0.0056
2.4	0.15	.6	1	1	109	40.1	0.188	0.188	0.029	0.0054
2.6	0.15	.6	1	1	103	40.1	0.179	0.179	0.03	0.0055
2.8	0.16	.6	1	1	110	40.2	0.189	0.189	0.031	0.0057
3	0.15	.6	1	1	103	40.1	0.179	0.179	0.031	0.0057
3.2	0.15	.6	1	1	109	40.3	0.187	0.187	0.03	0.0055
3.4	0.14	.6	1	1	90	40.4	0.157	0.157	0.029	0.005
3.6	0.14	.6	1	1	74	40.2	0.133	0.133	0.028	0.0041
3.8	0.12	.6	1	1	42	40.3	0.083	0.083	0.026	0.0028
4	0.03				---Effective Waters Edge 50% --				0.015	0.0006
Right Bank										

Meter : 1

Serial Number : 1-165323

Slope	Offset	Max
0.063	0.017	


Velocity maximum =0.214
Section Velocity Maximum=0.199 m/sec, Average Velocity=0.157 m/sec
10%
1 2 3 4 5 6 7 8 9 10 11 12 13 14
Section discharge maximum=0.00571 cumecs, total=0.0537 cumecs
Left Bank
Right Bank

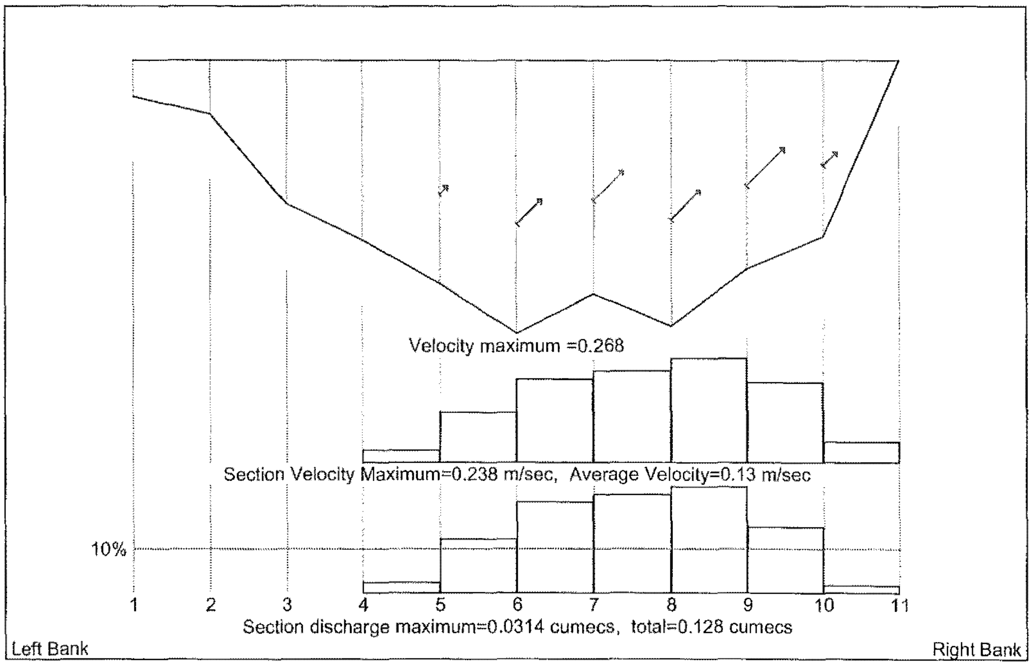
Gauging Report

Site No	: M36/5934
River at	: Cashmere Strm
Party	: Matt
Date	: 1/11/2002
Start time	: 14:30
End time	: 14:50
Total Discharge	: 0.1284 cumecs
Total Area	: 0.988 square metres
Maximum Depth	: 0.76 metres
Mean Velocity	: 0.13 m/sec
Surface Width	: 2 metres
Wetted Perimeter	: 2.68 metres
Hydraulic Radius	: 0.3687 metres
Verticals	: 11

Dist	Depth		Corr	M	Rev	Time	Vel	MeanVel	Area	Discharge
Left Bank										
1.2	0.1				--- Waters Edge --					
1.4	0.15	.2	1	1	0	0	0	0	0.025	0
1.6	0.4	.2	1	1	0	0	0	0	0.055	0
1.8	0.5	.2	1	1	0	0	0	0	0.09	0
2	0.62	.6	1	1	27	41.7	0.058	0.058	0.112	0.0032
2.2	0.76	.6	1	1	99	40	0.173	0.173	0.138	0.0159
2.4	0.65	.6	1	1	123	40.2	0.21	0.21	0.141	0.027
2.6	0.74	.6	1	1	121	40.1	0.207	0.207	0.139	0.029
2.8	0.58	.6	1	1	160	40.1	0.268	0.268	0.132	0.0314
3	0.49	.6	1	1	51	40.2	0.097	0.097	0.107	0.0195
3.2	0				---Effective Waters Edge 50% --				0.049	
Right Bank										

Meter : 1
Serial Number : 1-165323

Slope	Offset	Max
0.063	0.017	



Velocity maximum =0.268
Section Velocity Maximum=0.238 m/sec, Average Velocity=0.13 m/sec
10%
1
2
3
4
5
6
7
8
9
10
11
Section discharge maximum=0.0314 cumecs, total=0.128 cumecs
Left Bank
Right Bank

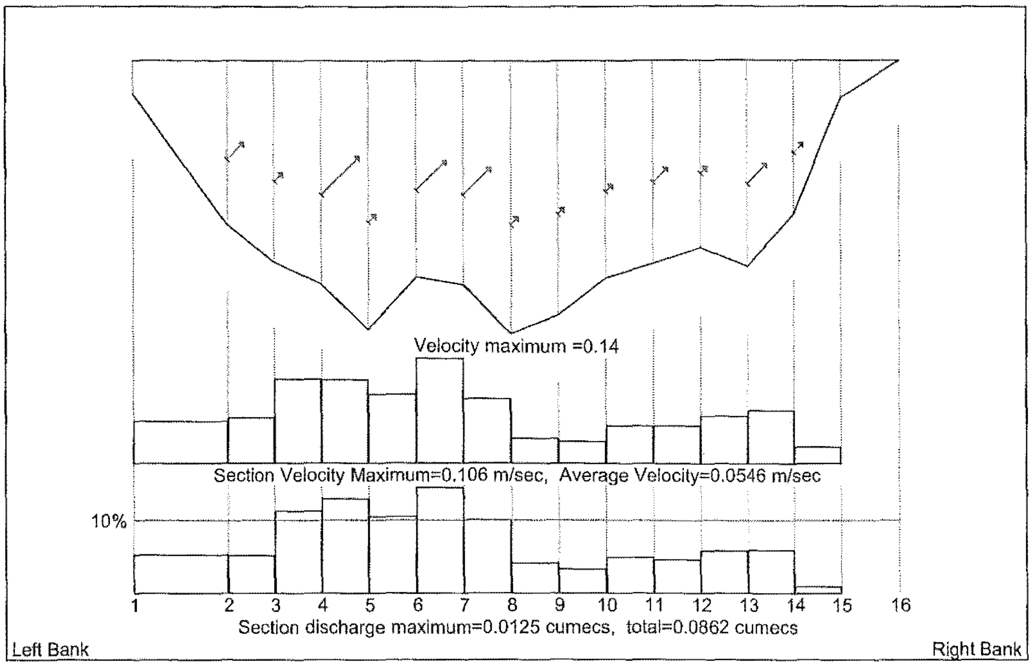
Gauging Report

Site No	: M36/7231
River at	: Cashmere Strm
Party	: Matt
Date	: 1/11/2002
Start time	: 15:00
End time	: 15:20
Total Discharge	: 0.08618 cumecs
Total Area	: 1.579 square metres
Maximum Depth	: 0.73 metres
Mean Velocity	: 0.0546 m/sec
Surface Width	: 3.25 metres
Wetted Perimeter	: 3.807 metres
Hydraulic Radius	: 0.4146 metres
Verticals	: 16

Dist	Depth	Corr		M	Rev	Time	Vel	MeanVel	Area	Discharge
Left Bank										
1.2	0.09				---Effective Waters Edge 70% --					
1.6	0.44	.6	1	1	29	41.1	0.061	0.061	0.106	0.0046
1.8	0.54	.6	1	1	10	44.2	0.031	0.031	0.098	0.0045
2	0.6	.6	1	1	78	40.1	0.14	0.14	0.114	0.0097
2.2	0.72	.6	1	1	9	45.9	0.029	0.029	0.132	0.0111
2.4	0.58	.6	1	1	60	40.4	0.111	0.111	0.13	0.0091
2.6	0.6	.6	1	1	54	40.2	0.102	0.102	0.118	0.0125
2.8	0.73	.6	1	1	8	40.7	0.029	0.029	0.133	0.0087
3	0.68	.6	1	1	3	40.7	0.022	0.022	0.141	0.0036
3.2	0.58	.6	1	1	4	40.1	0.023	0.023	0.126	0.0028
3.4	0.54	.6	1	1	24	41.2	0.054	0.054	0.112	0.0043
3.6	0.5	.6	1	1	4	40.7	0.023	0.023	0.104	0.004
3.8	0.55	.6	1	1	36	40.1	0.074	0.074	0.105	0.0051
4	0.41	.6	1	1	11	40	0.034	0.034	0.096	0.0052
4.2	0.1	.2	1	1	0	0	0	0	0.051	0.0009
4.45	0				--- Waters Edge --				0.0125	
Right Bank										

Meter : 1
Serial Number : 1-165323

Slope	Offset	Max
0.063	0.017	



Velocity maximum =0.14
Section Velocity Maximum=0.106 m/sec, Average Velocity=0.0546 m/sec
10%
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Section discharge maximum=0.0125 cumecs, total=0.0862 cumecs
Left Bank
Right Bank

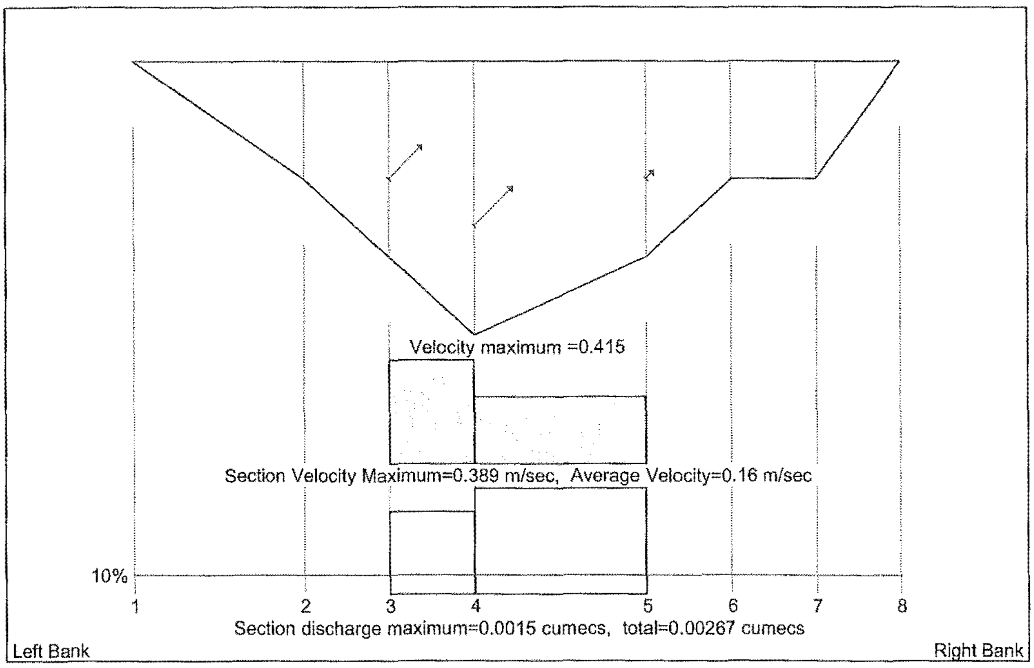
Gauging Report

Site No	: M36/7314
River at	: Cashmere Strm
Party	: Matt
Date	: 1/11/2002
Start time	: 16:50
End time	: 17:10
Total Discharge	: 0.002672 cumecs
Total Area	: 0.01675 square metres
Maximum Depth	: 0.07 metres
Mean Velocity	: 0.1595 m/sec
Surface Width	: 0.45 metres
Wetted Perimeter	: 0.4762 metres
Hydraulic Radius	: 0.03517 metres
Verticals	: 8

Dist	Depth	Corr	M		Rev	Time	Vel	MeanVel	Area	Discharge
Left Bank										
1.05	0				--- Waters Edge --					
1.15	0.03				--- Sounding --				0.0015	
1.2	0.05	.6	1	1	220	40.1	0.363	0.363	0.002	0
1.25	0.07	.6	1	1	253	40	0.415	0.415	0.003	0.0012
1.35	0.05	.6	1	1	44	40.1	0.086	0.086	0.006	0.0015
1.4	0.03				--- Sounding --				0.002	
1.45	0.03				--- Sounding --				0.0015	
1.5	0				--- Waters Edge --				0.0008	
Right Bank										

Meter : 1
Serial Number : 1-165323

Slope	Offset	Max
0.063	0.017	


Velocity maximum =0.415
Section Velocity Maximum=0.389 m/sec, Average Velocity=0.16 m/sec
10%
1
2
3
4
5
6
7
8
Section discharge maximum=0.0015 cumecs, total=0.00267 cumecs
Left Bank
Right Bank

Appendix H: V-Notch Weir Information

V-notch Weir Flow

Introduction

Weirs are typically installed in open channels such as streams to determine discharge (flowrate). The principle is that discharge is directly related to the water depth above the crotch (bottom) of the V; this distance is the head (h). The V-notch design causes small changes in discharge to have a large change in depth allowing more accurate head measurement than with a rectangular weir.

General Equation 1

$$Q = \frac{8}{15}\sqrt{2g}\cdot C_e \cdot \tan\frac{\alpha}{2}\cdot (h_e)^{\frac{5}{2}}$$

where:

C_e= Discharge Constant

H_e=Effective head given h+k

General Equation 2 – fully contracted weir

$$Q = \frac{8}{15}\sqrt{2g}\cdot C \cdot \tan\frac{\alpha}{2}\cdot (h)^{\frac{5}{2}}$$

For 90° V-Notch

$$\tan\frac{90}{2} = 1$$

$$\Rightarrow Q = \frac{8}{15}\sqrt{2g}\cdot C_e \cdot (h_e)^{\frac{5}{2}}$$

$$or$$

$$\Rightarrow Q = \frac{8}{15}\sqrt{2g}\cdot C \cdot (h)^{\frac{5}{2}}$$

Table of Ce and K Values:

Angle (degrees)	40	60	80	90
C_e	0.582	0.576	0.576	0.578
K_e (mm)	1.8	1.2	0.9	0.8
K_e (m)	0.018	0.012	0.009	0.008

From hydrologists field manual

Extract from LMNO Engineering, Research and Software Ltd:

Formula for C_e and k values:

$$C_e = 0.607165052 - 0.000874466963\ Ø + 6.10393334\times10^{-6}\ Ø^2$$
$$k(m) = 0.004416633 - 0.000103496\ Ø + 1.00529E\text{-}06\ Ø^2 - 3.23745E\text{-}09\ Ø^3$$

where Ø is the notch angle in degrees

Head (h) should be measured at a distance of at least 4h upstream of the weir.

It doesn't matter how thick the weir is except where water flows over the weir through the "V." The weir should be between 0.8 to 2 mm thick in the V. If the bulk of the weir is thicker than 2mm, the downstream edge of the V can be chamfered at an angle greater than 45° (60° is recommended) to achieve the desired thickness of the edges. You want to avoid having water cling to the downstream face of the weir.

Water surface downstream of the weir should be at least 6 cm below the bottom of the V to allow a free flowing waterfall.

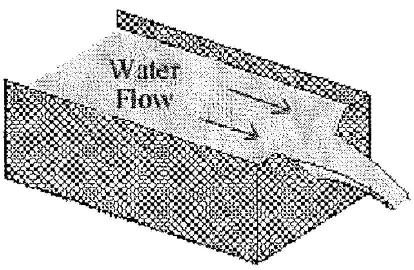
Measured head (h) should be greater than 6 cm due to potential measurement error at such small heads and the fact that the nappe (waterfall) may cling to the weir.

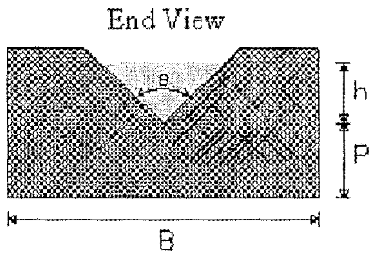
The equations have been developed for h< 38 cm and h/P<2.4..

The equations have been developed for fully contracted V-notch weirs which means h/B should be <= 0.2.

The average width of the approach channel (B) should be > 91 cm
The bottom of the "V" should be at least 45 cm above the bottom of the upstream channel.

If the weir does not achieve some of the above criteria, you may have a "partially contracted V-notch weir" where h/B needs only to be <= 0.4, the bottom of the "V" only needs to be 10 cm above the bottom of the upstream channel, the approach channel only needs to be 61 cm wide, and h can be up to 61 cm instead of 38 cm. Partially contracted weirs use a different graph for C which is a function of h/P and P/B and is only valid for a notch angle of 90°. In the graph (not shown - see USBR, 1997), C varies from 0.576 to 0.6; whereas, for a fully contracted 90° notch, C is 0.578 from our graph shown above. Our calculation does not account for partially contracted weirs, but for most practical purposes the difference in C is inconsequential.



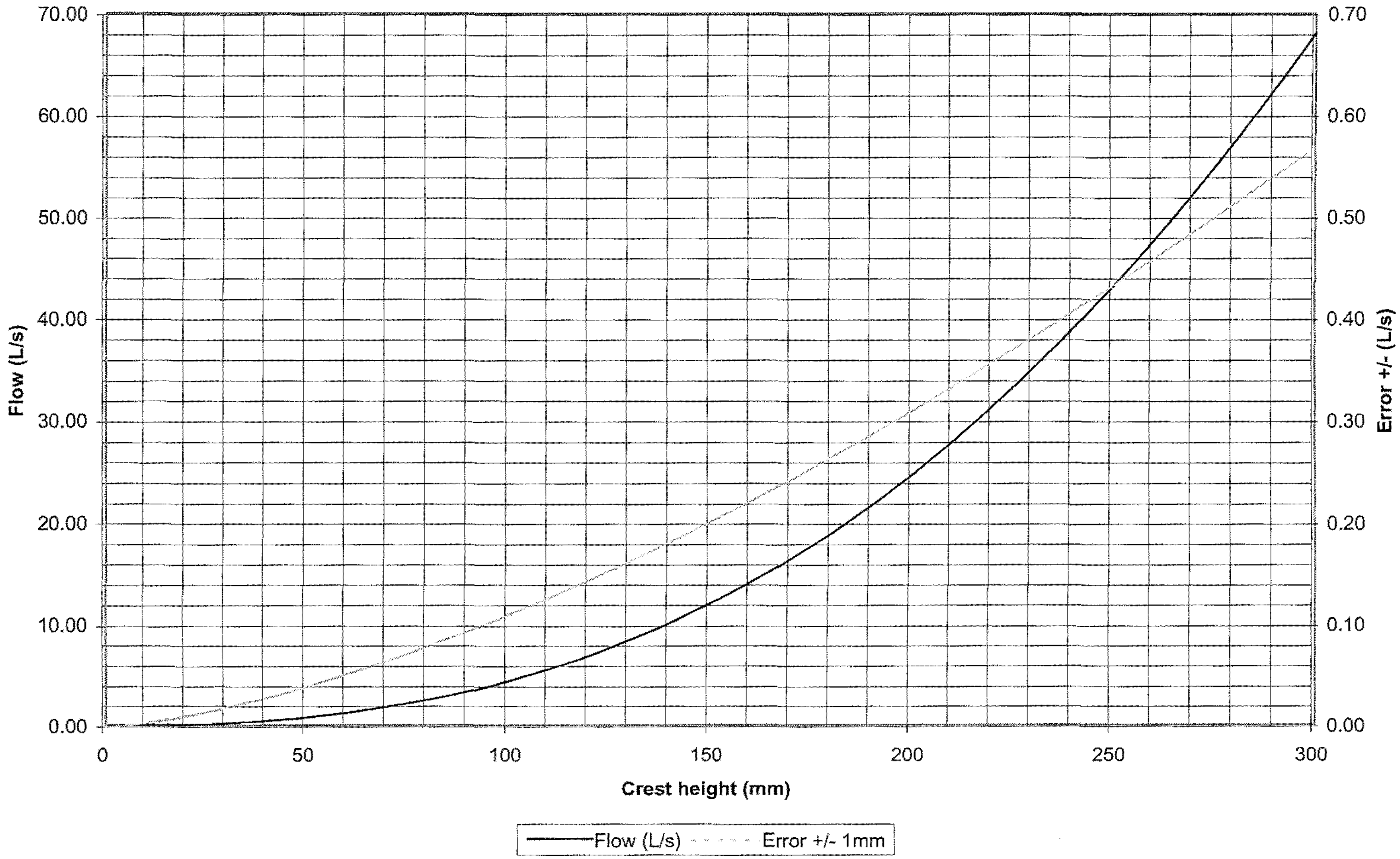


Fluid mechanics approximation for a V-notch Weir:

$$Q = 1.38H^{2.50}$$

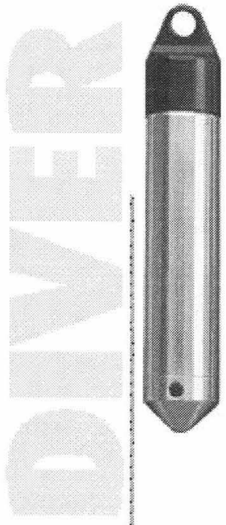
From Fluid Mechanics, Streeter & Wylie (1981)

90 degree V-notch Weir Flow Curve



H4

Appendix I: Equipment Specifications



Van Essen Diver Technical specifications

General Diver Specifications
Sample rate* 0.5 sec to 99 hrs
Memory 2 x 24,000 measurements (non-volatile)
Material housing stainless steel (AISI 316L)
Material pressure sensor ceramic
Temperature range -20°C to 80°C
- accuracy ±0.1°C
- resolution 0.01 °C
- compensation range -10°C to 40°C
Battery life 8-10 years
Dimensions Ø22 mm, length 125 mm
Weight 160 grams

Type	Calibrated Range	Usable Range	Accuracy**	Resolution
DI240	5 m water column	4 m water column	+/-0.1% FS	1 mm
DI241	10 m water column	9 m water column	+/-0.1% FS	2 mm
DI242	20 m water column	19 m water column	+/-0.1% FS	4 mm
DI243	30 m water column	29 m water column	+/-0.1% FS	6 mm
DI245	100 m water column	99 m water column	+/-0.1% FS	20 mm
DI250 (Baro)	1.5 m water column	N/A	+/-0.3% FS	1 mm

* Different sample modes available for aquifer tests. ** Fully temperature compensated

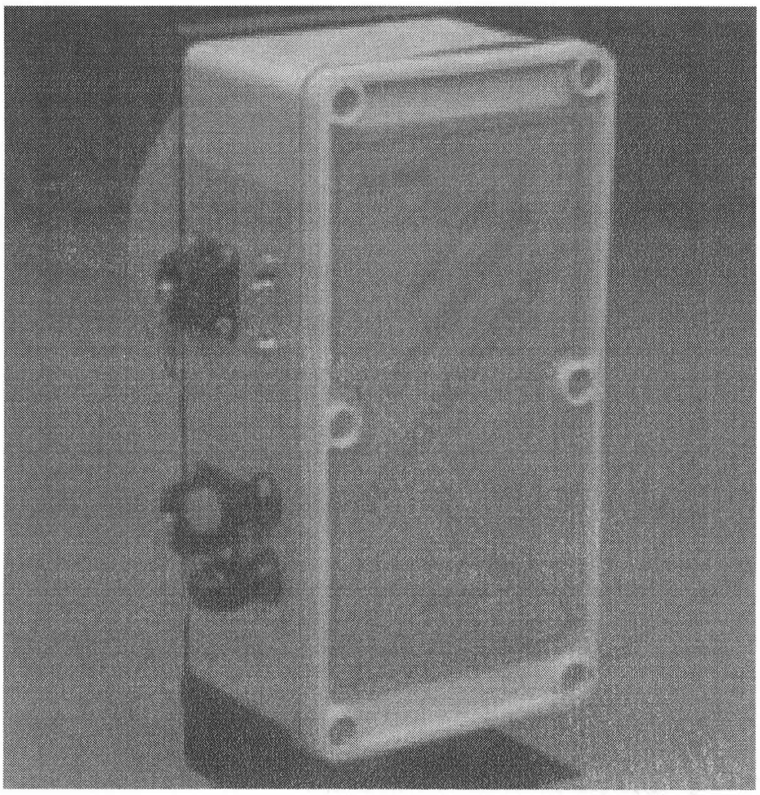
Hydrologger Water Level Recorder

The NIWA Hydrologger 2001 data recorder consists of a 128 K data logger and a low torque optical shaft encoder integrated into a single package to provide a self-contained hydrometric data collection system.

The Hydrologger incorporates the powerful UNIDATA micrologger and can provide approximately 50,000 water level and rainfall records. The Hydrologger's optical shaft encoder has a range of 0–49 m, providing 1mm data resolution from its standard 375 mm beaded float line pulley. The beaded line can optionally be replaced with a standard 100 or 300 mm punched float tape input pulley assembly to provide data with a resolution of 0.2 mm or 0.6 mm respectively.

Data from the Hydrologger is downloaded via its built-in RS232 port or, if required, can be remotely downloaded via telemetry systems.

The Hydrologger is fully compatible with the UNIDATA range of support software and is user-programmable for such features as recording interval and onboard data manipulation. Data is TIDEDA compatible using NIWA Tlogger software.



Hydrologger Specifications

Dimensions	H 240, W 135, D 120 mm High impact PVC enclosure
Protection	Rated IP 65
Power supply	Voltage 12 VDC nom Current (Quiesc)100 mA Current (Scan) 30 mA
Micrologger Inputs	1 x HS serial (encoder) 1 x 20kHz counter (rainfall)
Memory	128k byte CMOS RAM
Log interval	0.125 sec to 1 week
Scan rate	0.125 sec to 5 min, programmable
Encoder range	0–49 metres (375 mm pulley)
Resolution	1 mm (500 mm pulley assembly)
Shaft dia.	6.35 mm
Tracking	500 mm/sec max.
Indicator	1 x scan LED
Data output	RS232C, 300–76800 baud

Micronics Acoustic Flow Meter – Portaflow 300

PORTAFLOW™ 300 SPECIFICATION

ENCLOSURE:

IP66 Protection Class	Material	High density P.U. foam
	Weight	< 1.5 Kg
	Dimensions	275 x 150 x 55 mm
	Display	240 x 64 graphics LCD with backlight
	Keypad	IP68 16 key tactile membrane
	Connections	IP66 Lemo connectors
	Temperature range	0°C to +50°C operating -10° to +50°C storage

SUPPLY VOLTAGE:

Power supply/charger	Input	100-260 VAC ±10% @ 50/60 Hz Max. 9 watts
	Output	9VDC unregulated

BATTERY PACK:

Internal Batteries	5 x 4/3 AA nickel metal hydride	24-30 hrs continuous operating on fully charged battery cells
	Recharge time	10-16 hours

External battery can be connected to the Portaflow 300 for remote flow monitoring (contact Micronics)

OUTPUTS:

Languages (optional)	English/German/French	
Display	Volumetric flow units	m^3, litres, gallons (Imperial and US)
	Velocity units	metres/sec, feet/sec
	Flow velocity range	0.2...12 m/sec to 4 significant figures
	Total volume	12 Digits - forward and reverse
	Continuous battery level indication	
	Continuous signal level indication	
	ERROR messages	
Analogue	4-20mA into 750 Ω	User definable scaling
	Resolution	0.1% of full scale
Pulse	5 Volts	
	Max. 1 pulse per second	User definable scaling
Printer/Terminal	Serial RS232-C	inc. handshaking User definable scaling

DATA LOGGER:

	Memory capacity	100K (50,000 readings)
Output	Via RS232 or displayed graphically	
Logs	Block data storage with text and graphic display, transferred to Microsoft Windows or Micronics user compatible software package (optional)	

TRANSDUCER SETS	Pipe Size	Velocity Range
'A' (standard)	13 mm...115mm pipe	0.2 m/sec...8 m/sec
'B' (standard)	50 mm...1000mm pipe	0.2 m/sec...12 m/sec
'C' (optional)	300 mm...2000mm pipe	0..2 m/sec...7 m/sec
'D' (optional)	1000 mm...5000mm pipe	0.2 m/sec...7 m/sec
	Temperature Range 'A', 'B' 'C'	-20°C to +200°C standard
	Frequency	1MHz, 2MHz, 0.5MHz

PIPE MATERIALS

Any sonic conducting medium such as Carbon Steel, Stainless Steel, Copper, UPVC, PVDF Concrete Galvanised Steel, Mild Steel, Glass, Brass. Including Lined Pipes – Epoxy, Rubber, Steel, Plastic.

REPEATABILITY

± 0.5% with unchanged transducer position.

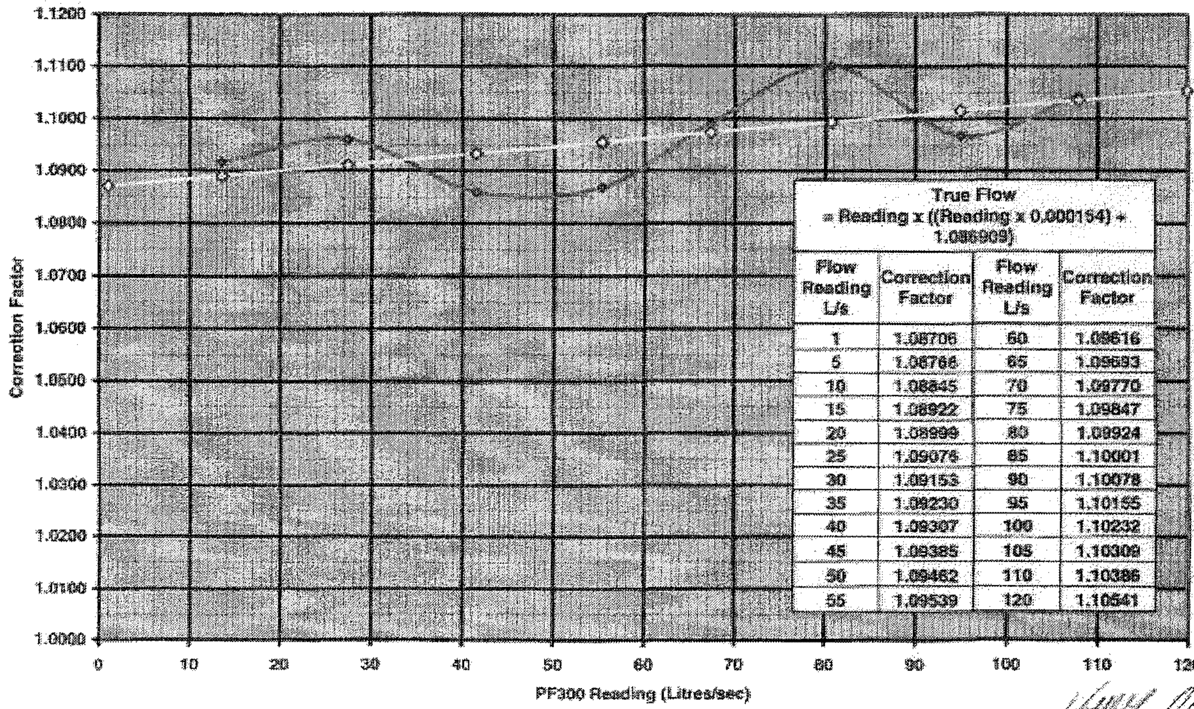
ACCURACY:

2% or ± 0.02 m/sec whichever is the greater. Accuracy achieved under ideal calibration conditions on a 4" plastic pipe. Specification assumes turbulent flow profile with Reynolds numbers above 4000.

Micronics reserve the right to alter any specification without notification

PF300 PortaFlow Meter (Serial No.0101)
Correction Factors

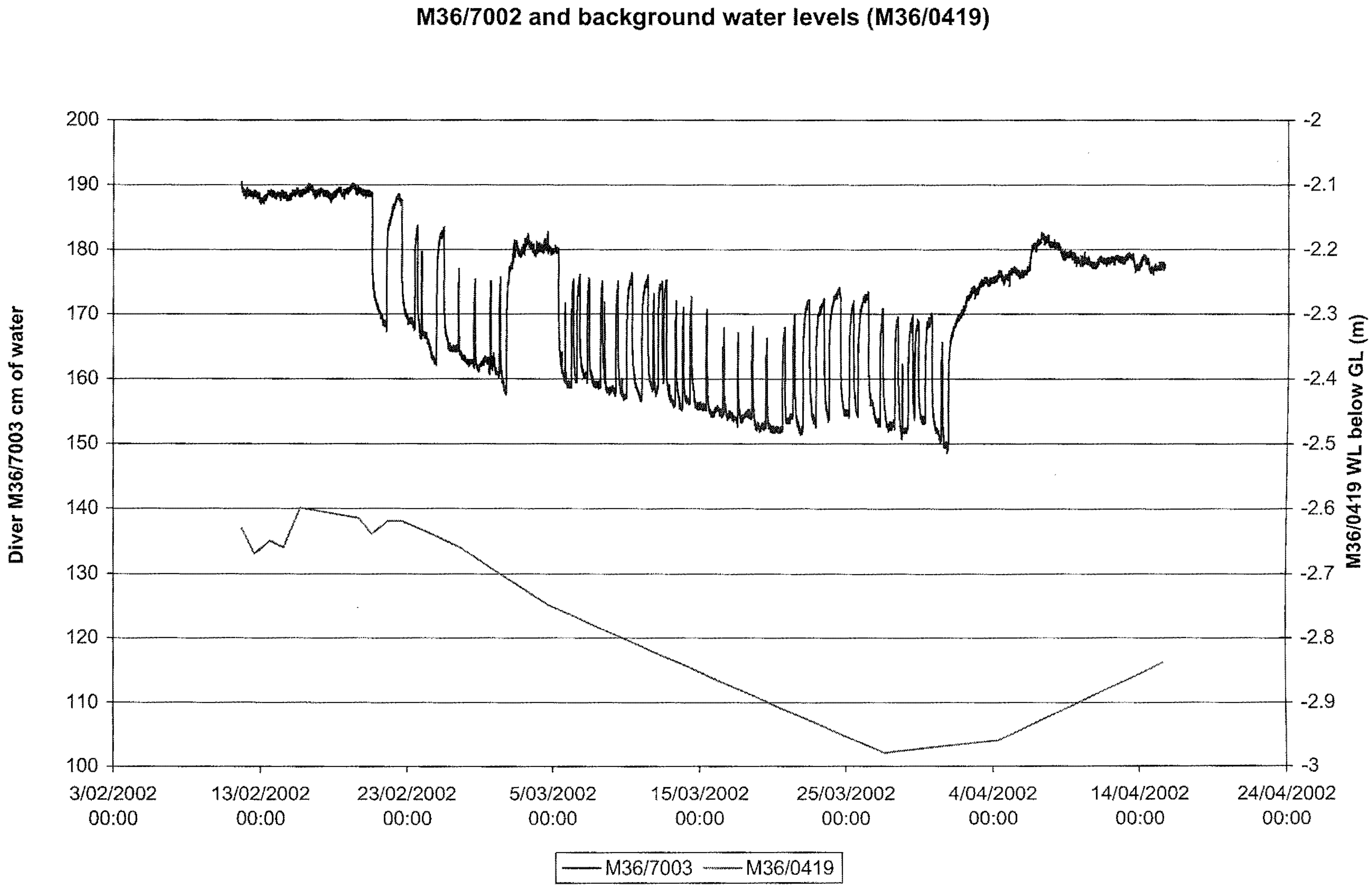
(Calibration Tests at University of Canterbury on 30-Aug-2002)



True Flow
= Reading x ((Reading x 0.000154) + 1.086909)

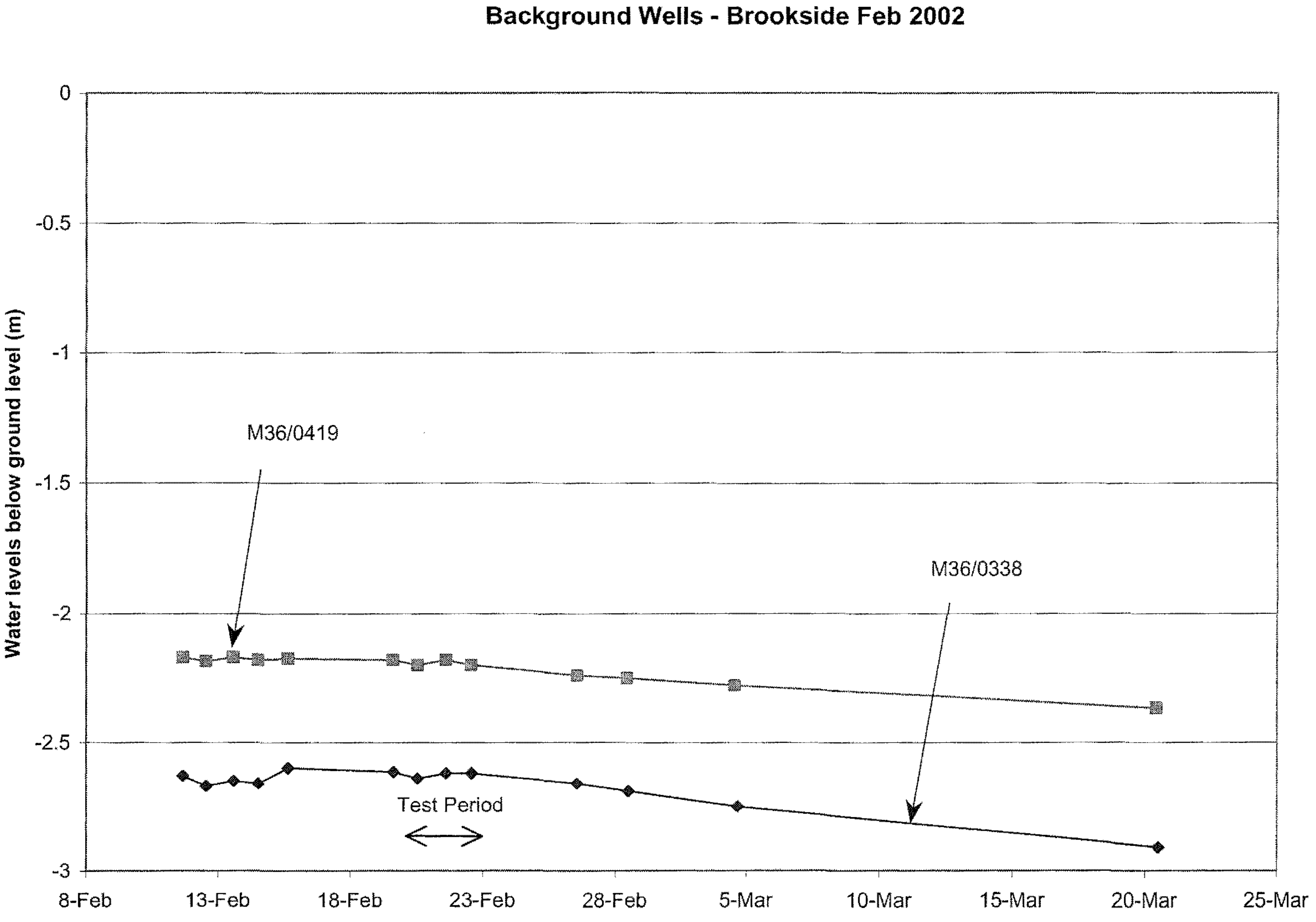
Flow Reading L/s	Correction Factor	Flow Reading L/s	Correction Factor
1	1.08706	60	1.09616
5	1.08766	65	1.09693
10	1.08845	70	1.09770
15	1.08922	75	1.09847
20	1.08999	80	1.09924
25	1.09076	85	1.10001
30	1.09153	90	1.10078
35	1.09230	95	1.10155
40	1.09307	100	1.10232
45	1.09385	105	1.10309
50	1.09462	110	1.10386
55	1.09539	120	1.10541

Appendix J: Background Water Levels


M36/7002 and background water levels (M36/0419)
Diver M36/7003 cm of water
M36/0419 WL below GL (m)
200
190
180
170
160
150
140
130
120
110
100
-2
-2.1
-2.2
-2.3
-2.4
-2.5
-2.6
-2.7
-2.8
-2.9
-3
3/02/2002 00:00
13/02/2002 00:00
23/02/2002 00:00
5/03/2002 00:00
15/03/2002 00:00
25/03/2002 00:00
4/04/2002 00:00
14/04/2002 00:00
24/04/2002 00:00
M36/7003
M36/0419

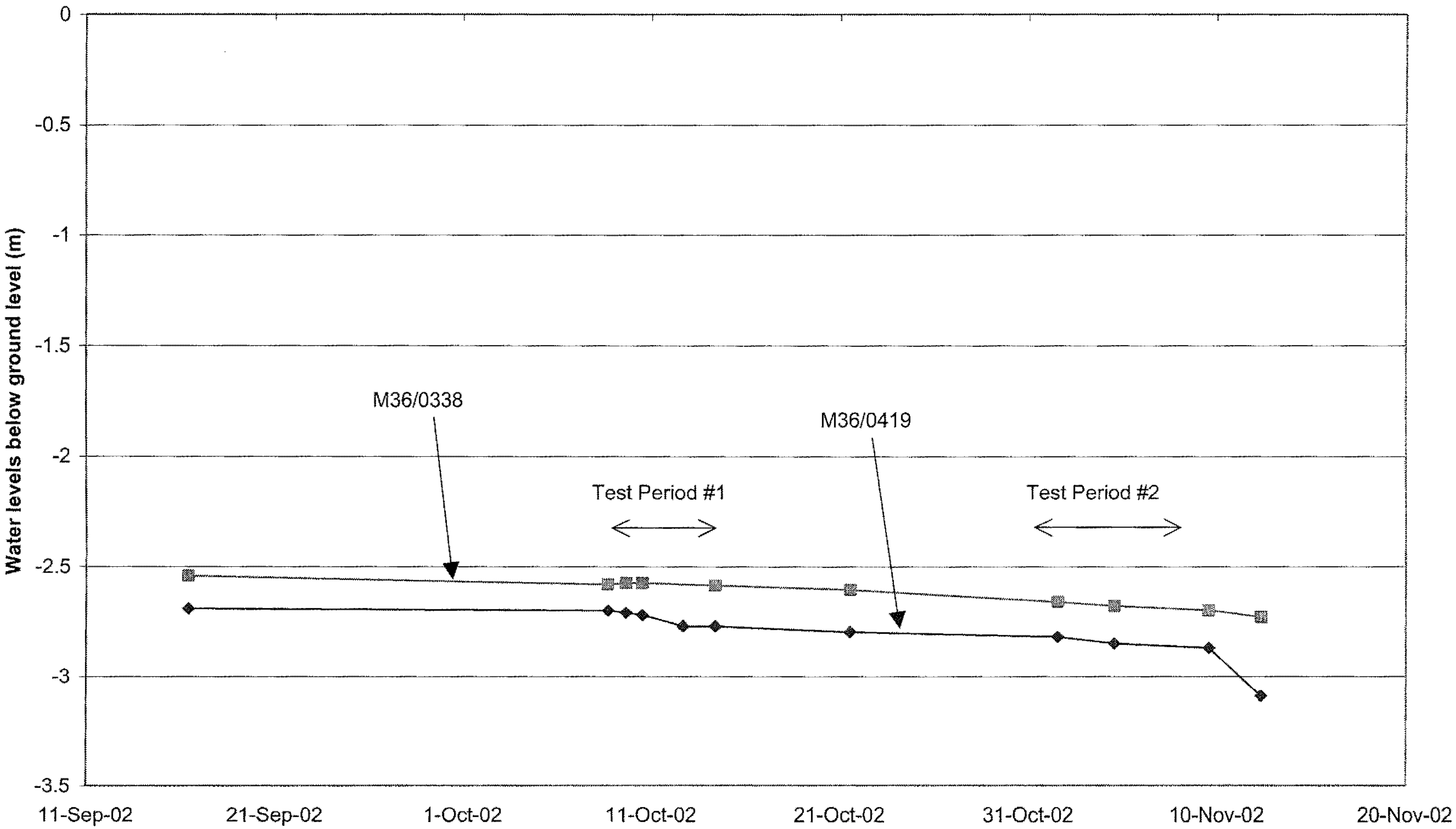
J1

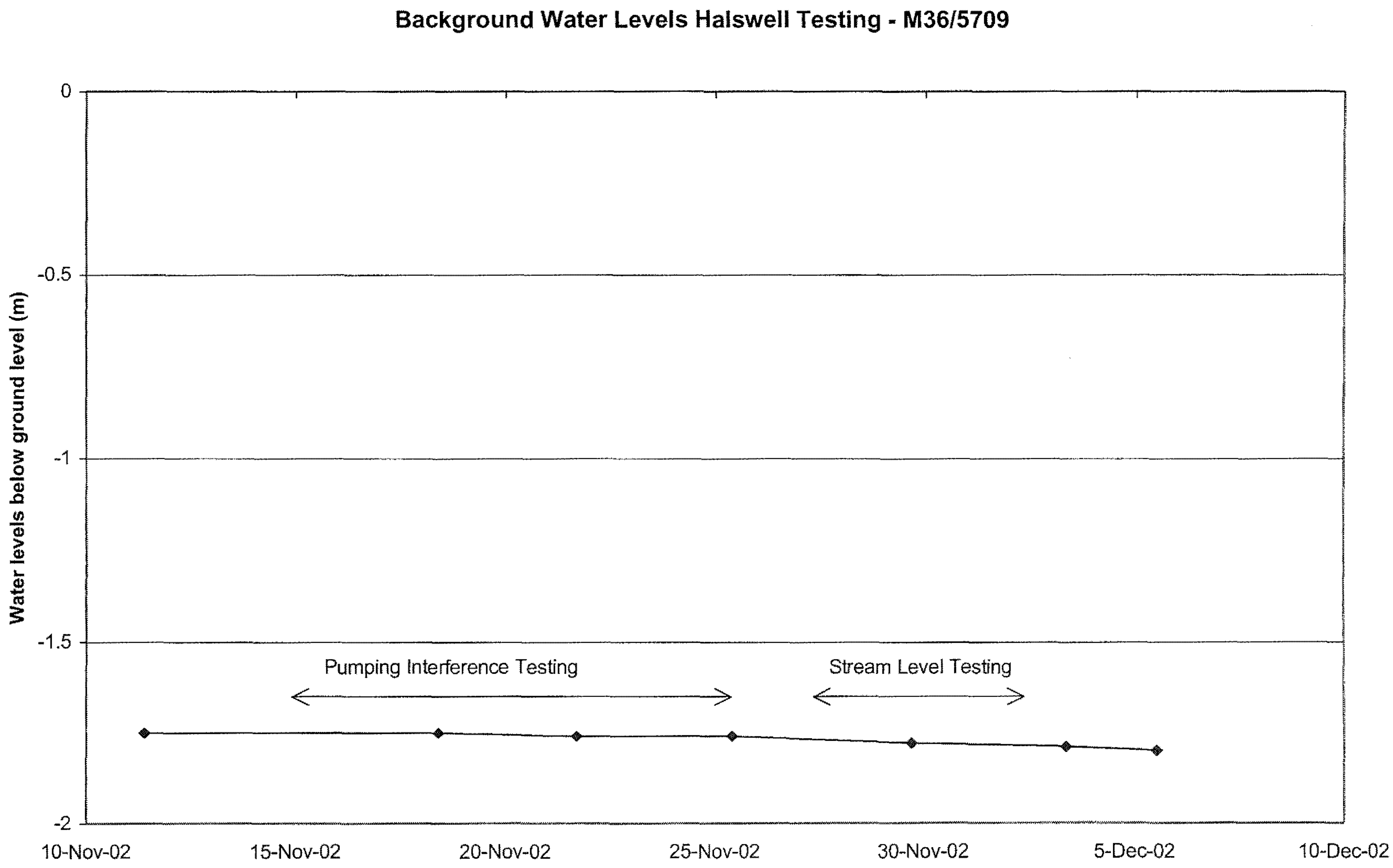
J2



Background Wells - Brookside Feb 2002
Water levels below ground level (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
8-Feb
13-Feb
18-Feb
23-Feb
28-Feb
5-Mar
10-Mar
15-Mar
20-Mar
25-Mar
M36/0419
M36/0338
Test Period

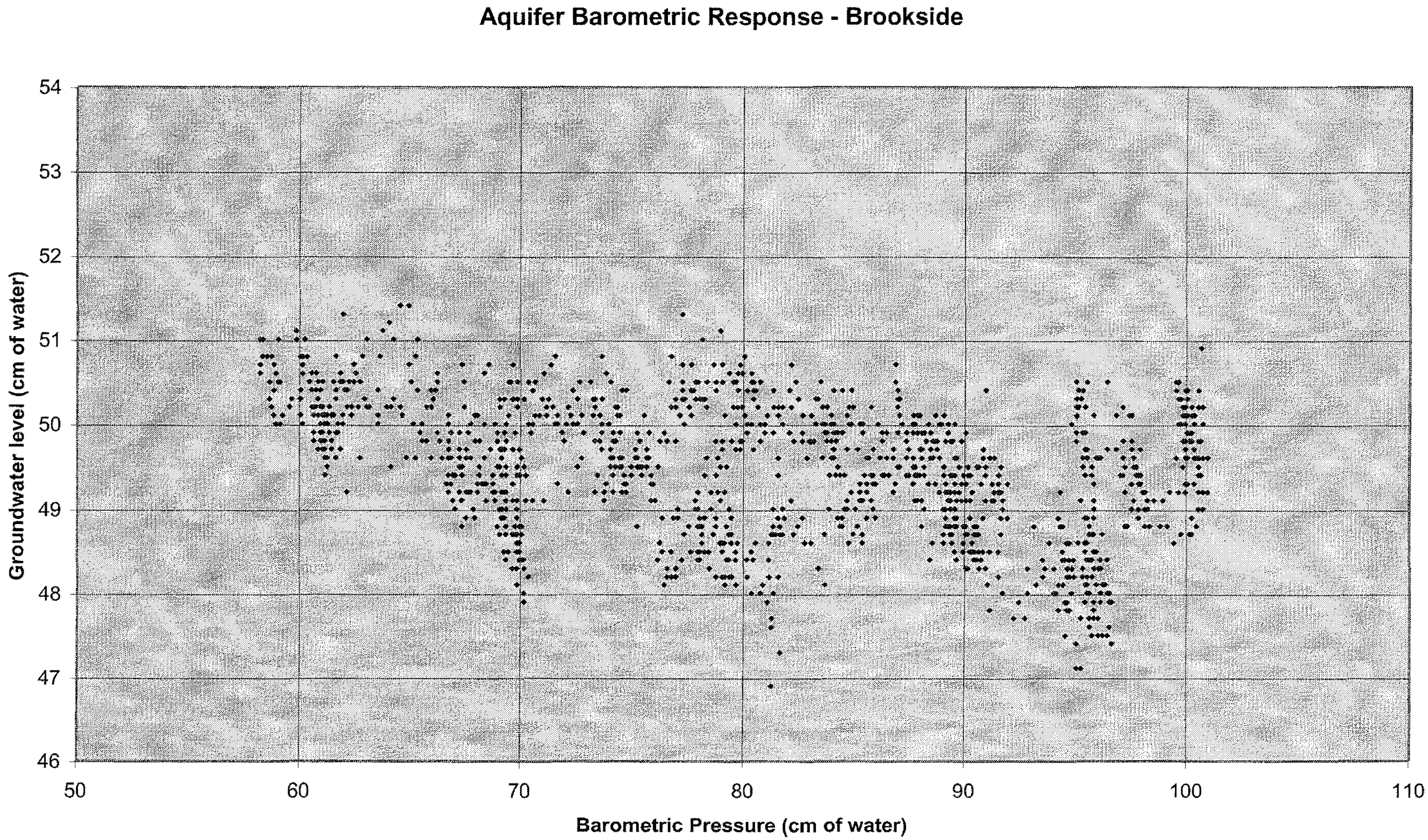
Background Water Levels Brookside Testing



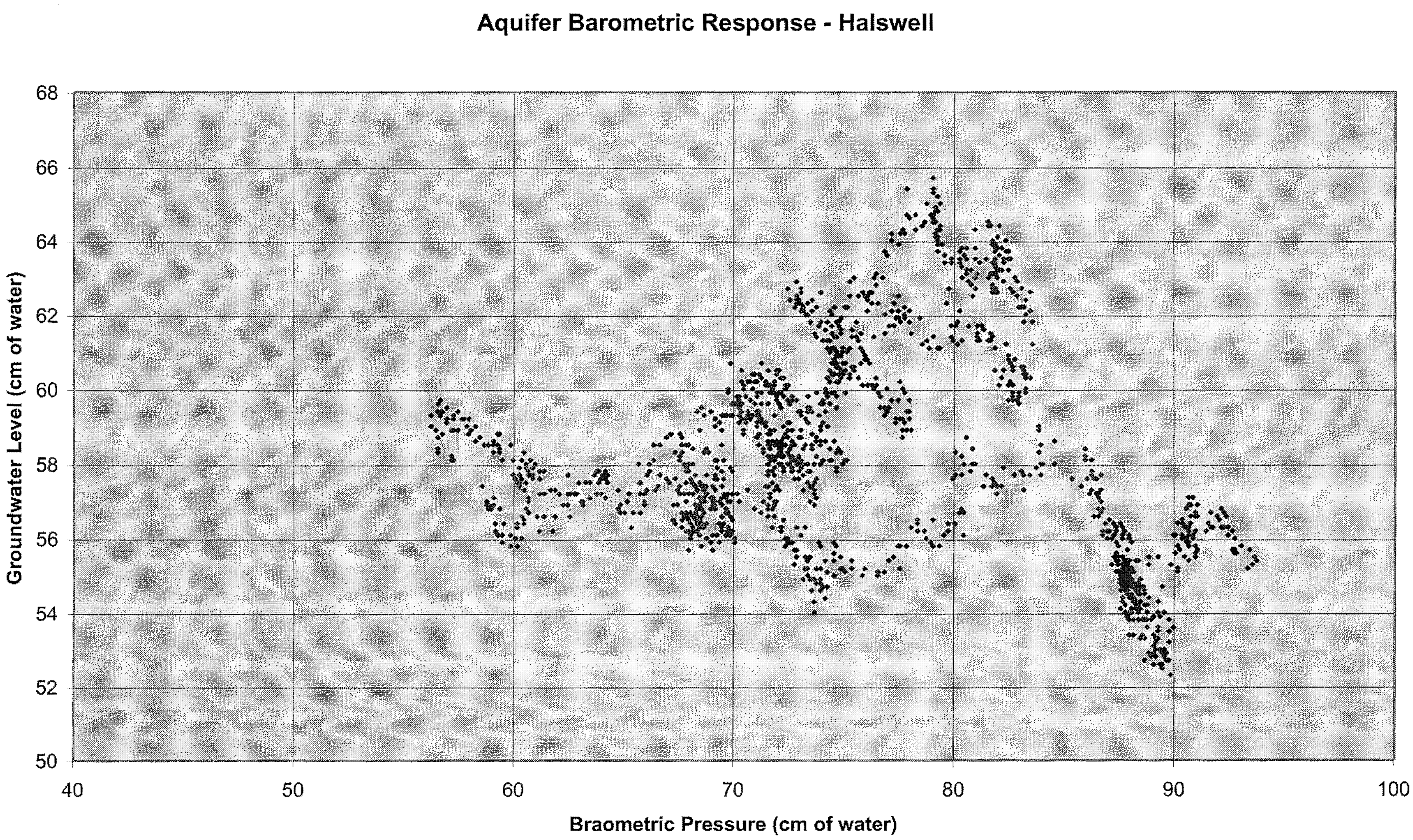

Background Water Levels Halswell Testing - M36/5709
Water levels below ground level (m)
0
-0.5
-1
-1.5
-2
10-Nov-02
15-Nov-02
20-Nov-02
25-Nov-02
30-Nov-02
5-Dec-02
10-Dec-02
Pumping Interference Testing
Stream Level Testing

J4

Appendix K: Barometric Efficiency

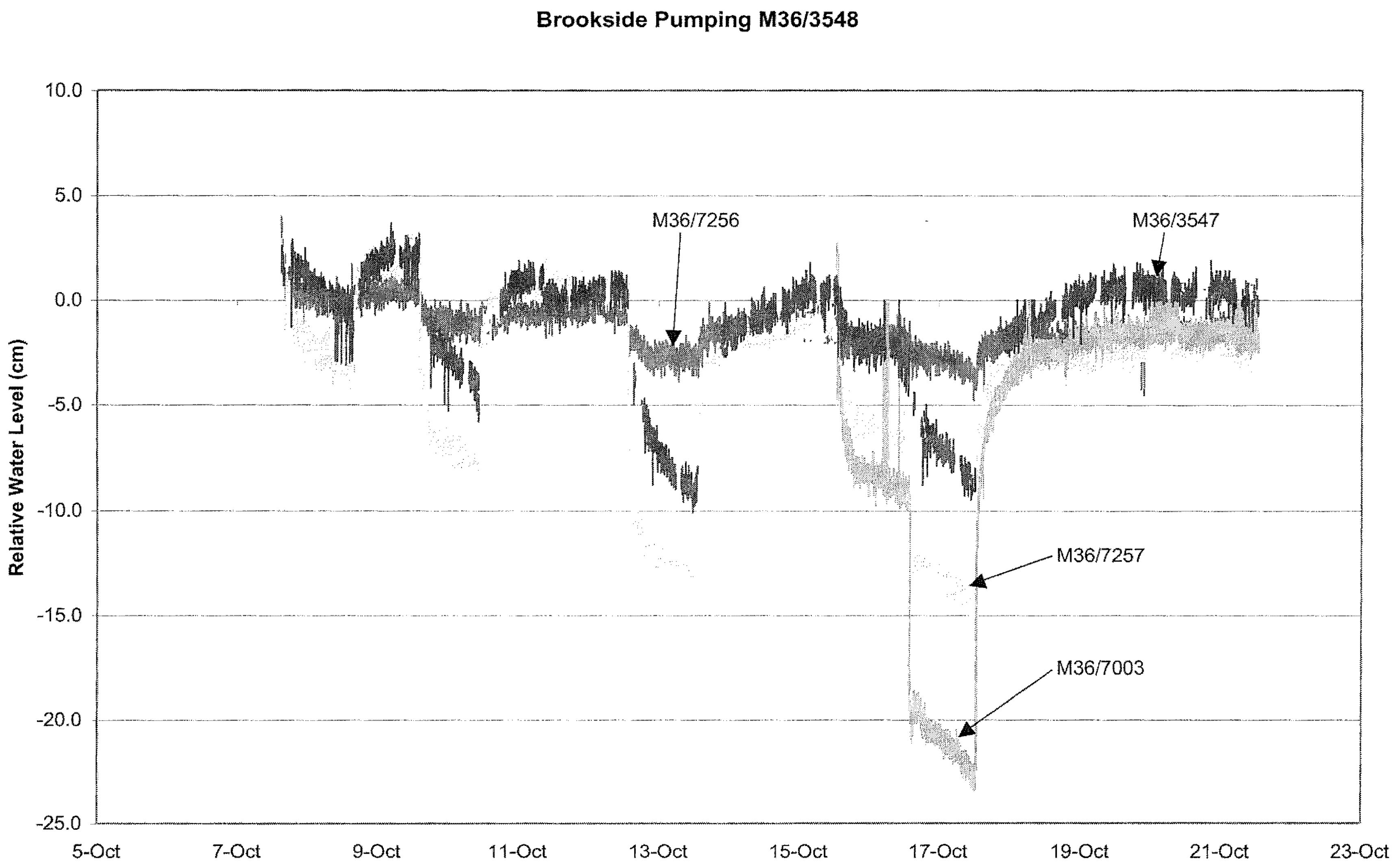

Aquifer Barometric Response - Brookside
Groundwater level (cm of water)
Barometric Pressure (cm of water)
54
53
52
51
50
49
48
47
46
50
60
70
80
90
100
110

K1

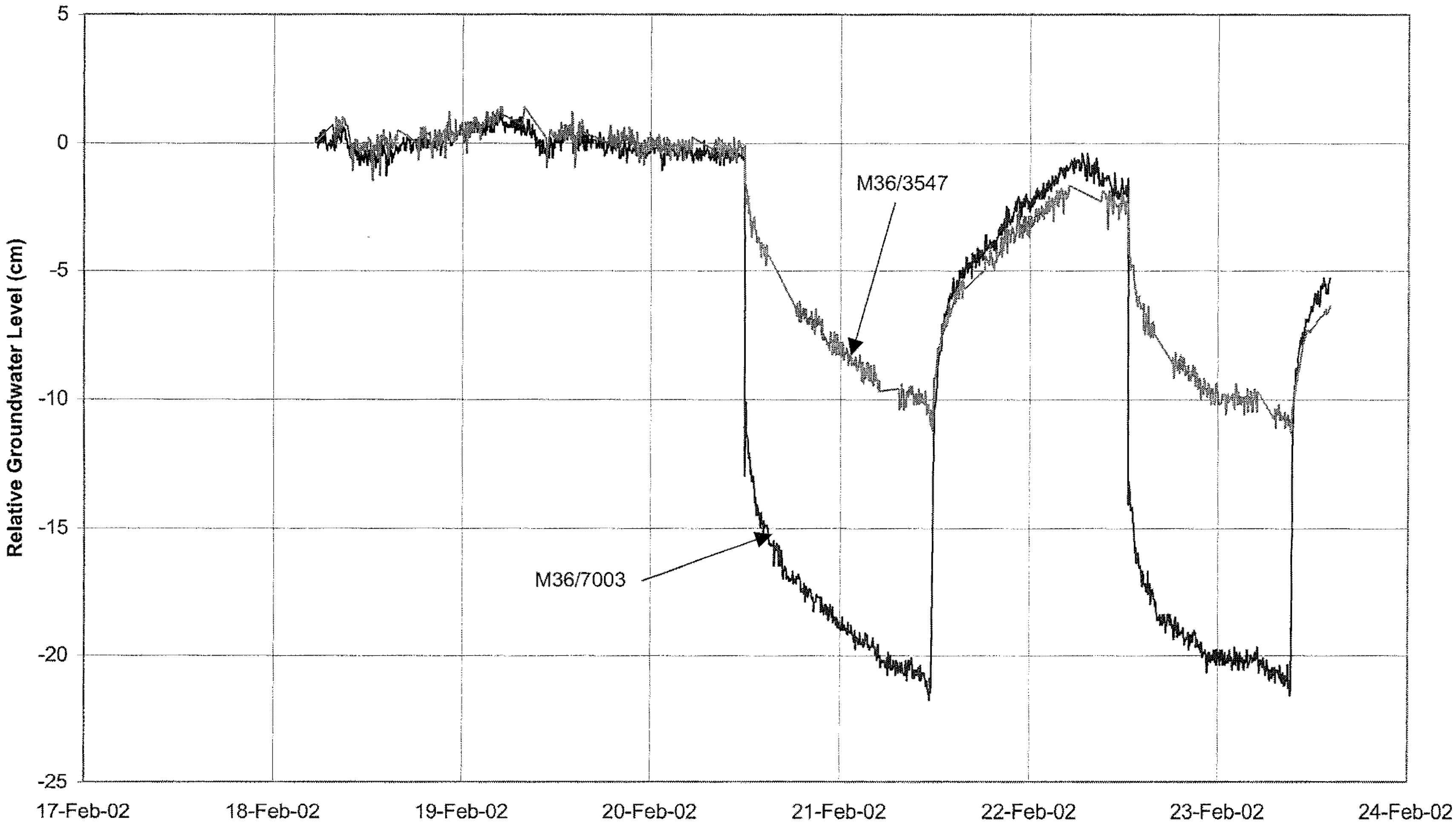

Aquifer Barometric Response - Halswell
Groundwater Level (cm of water)
Braometric Pressure (cm of water)
68
66
64
62
60
58
56
54
52
50
40
50
60
70
80
90
100

K2

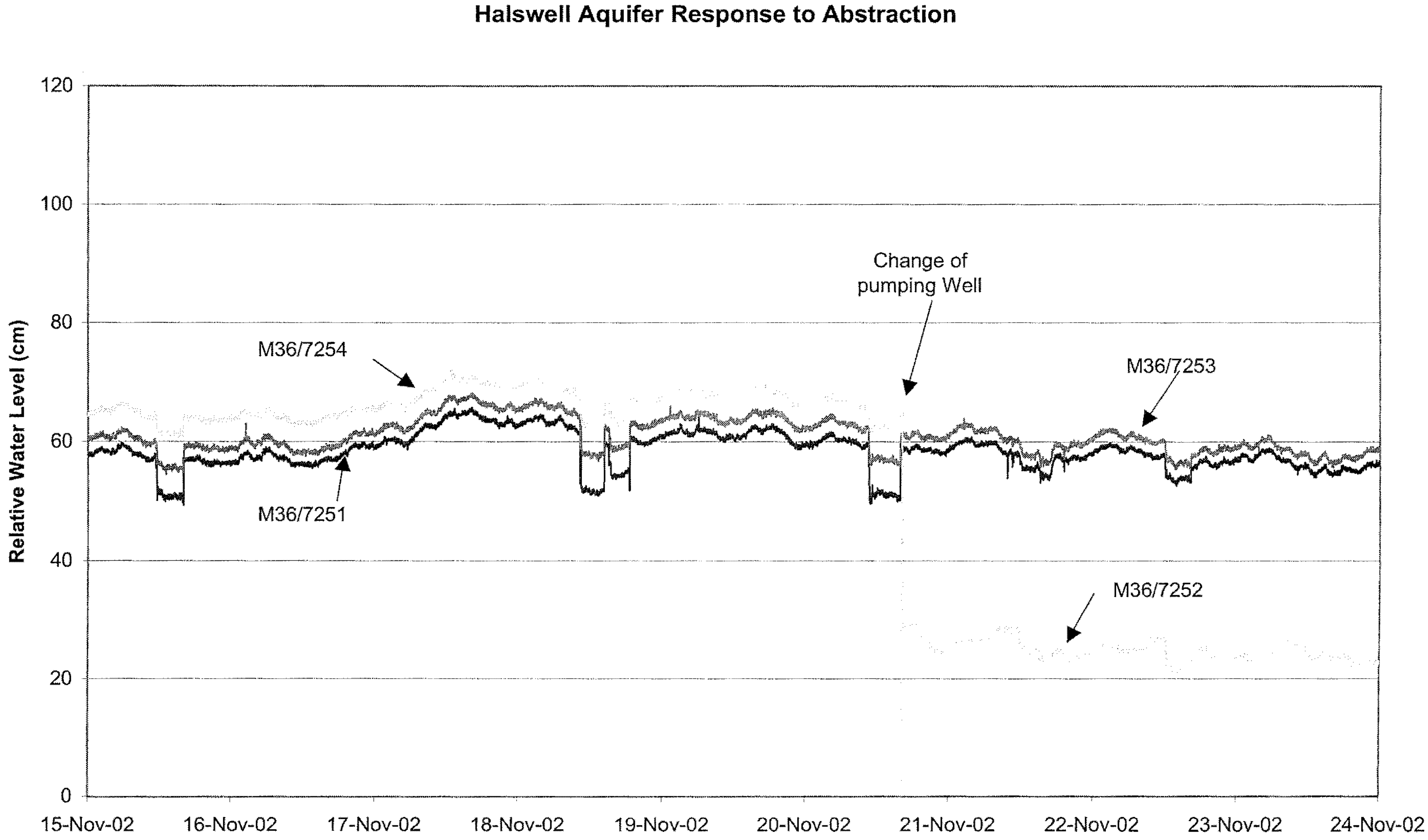
Appendix L: Aquifer Response


Brookside Pumping M36/3548
Relative Water Level (cm)
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
5-Oct
7-Oct
9-Oct
11-Oct
13-Oct
15-Oct
17-Oct
19-Oct
21-Oct
23-Oct
M36/7256
M36/3547
M36/7257
M36/7003

M36/3548, Brookside February 2002 @ 24 L/s

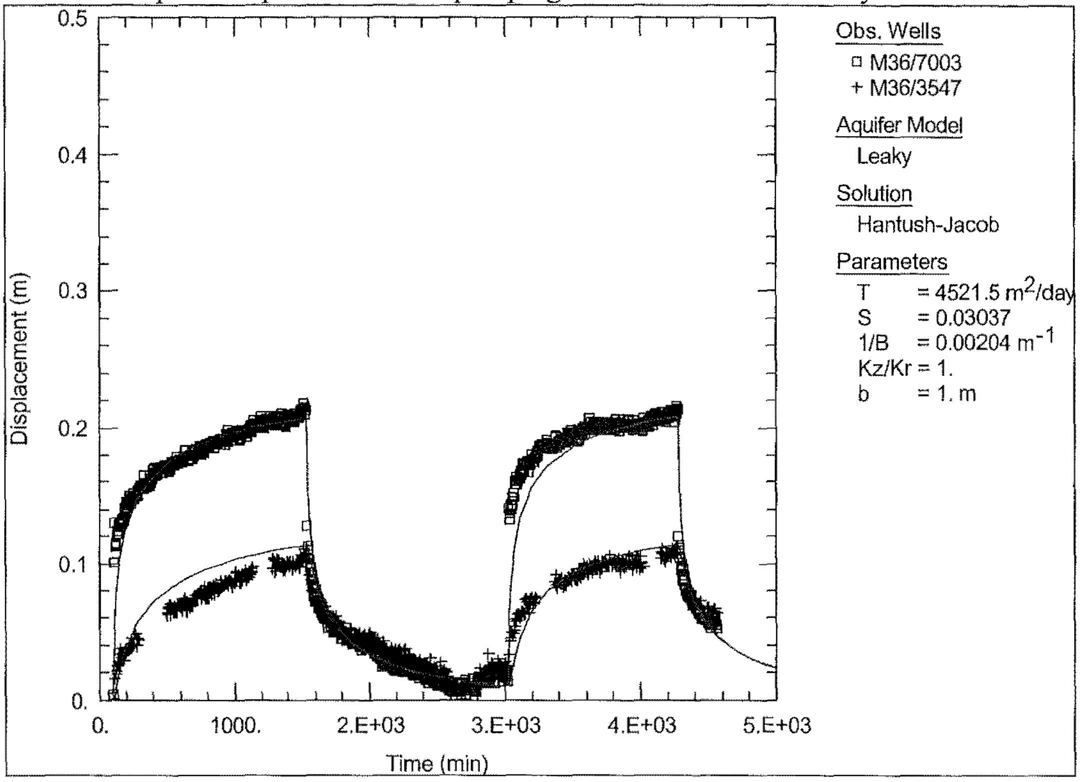


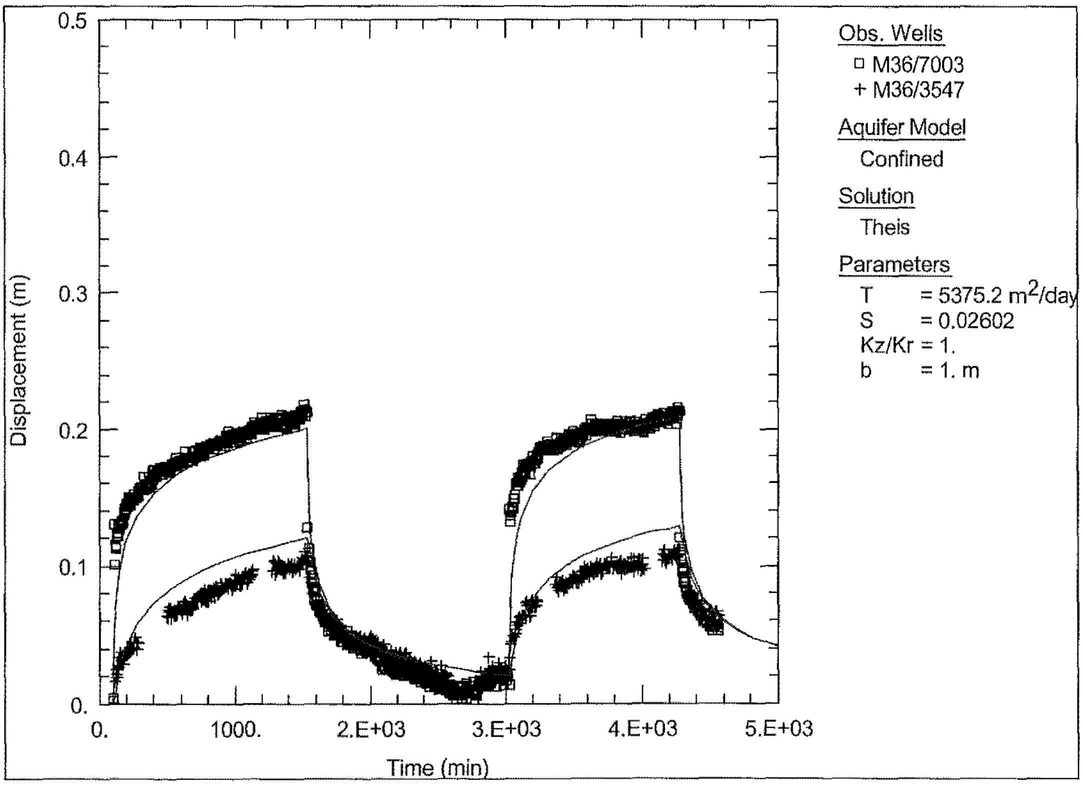
L3


Halswell Aquifer Response to Abstraction
Relative Water Level (cm)
120
100
80
60
40
20
0
15-Nov-02
16-Nov-02
17-Nov-02
18-Nov-02
19-Nov-02
20-Nov-02
21-Nov-02
22-Nov-02
23-Nov-02
24-Nov-02
Change of
pumping Well
M36/7254
M36/7251
M36/7253
M36/7252

Appendix M: Aquifer Test Analysis

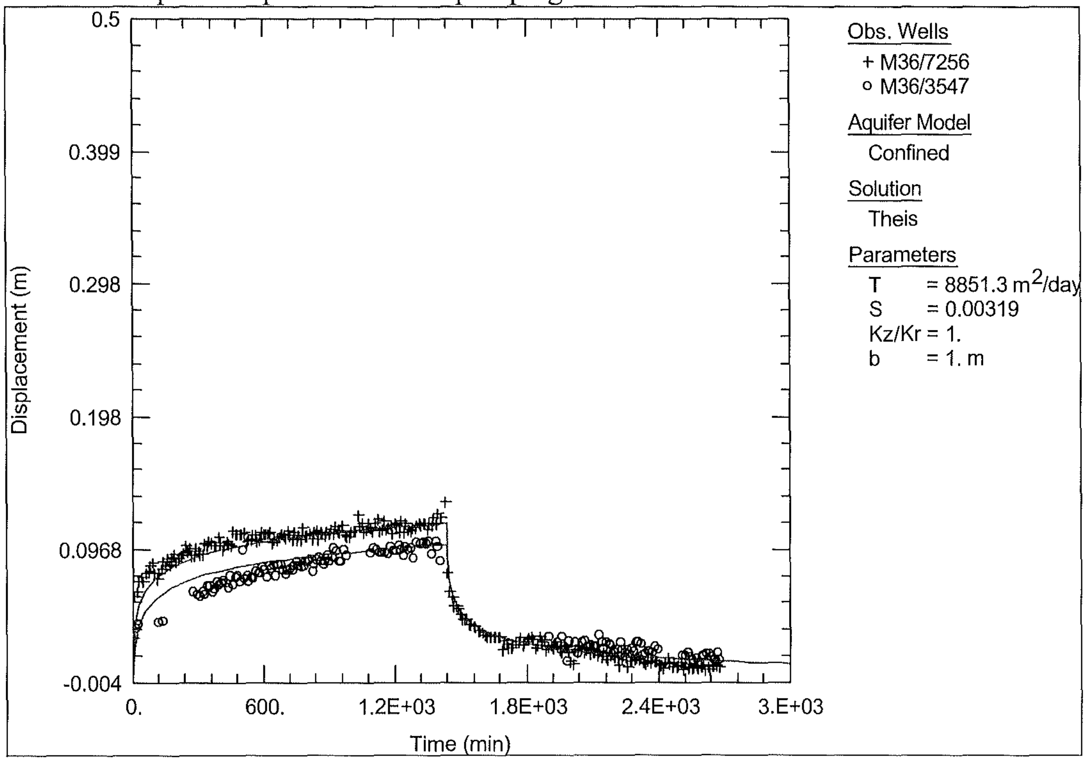
Aqtesolv analysis plots of:
Brookside aquifer response to 24 L/s pumping from M36/3548 February 2002

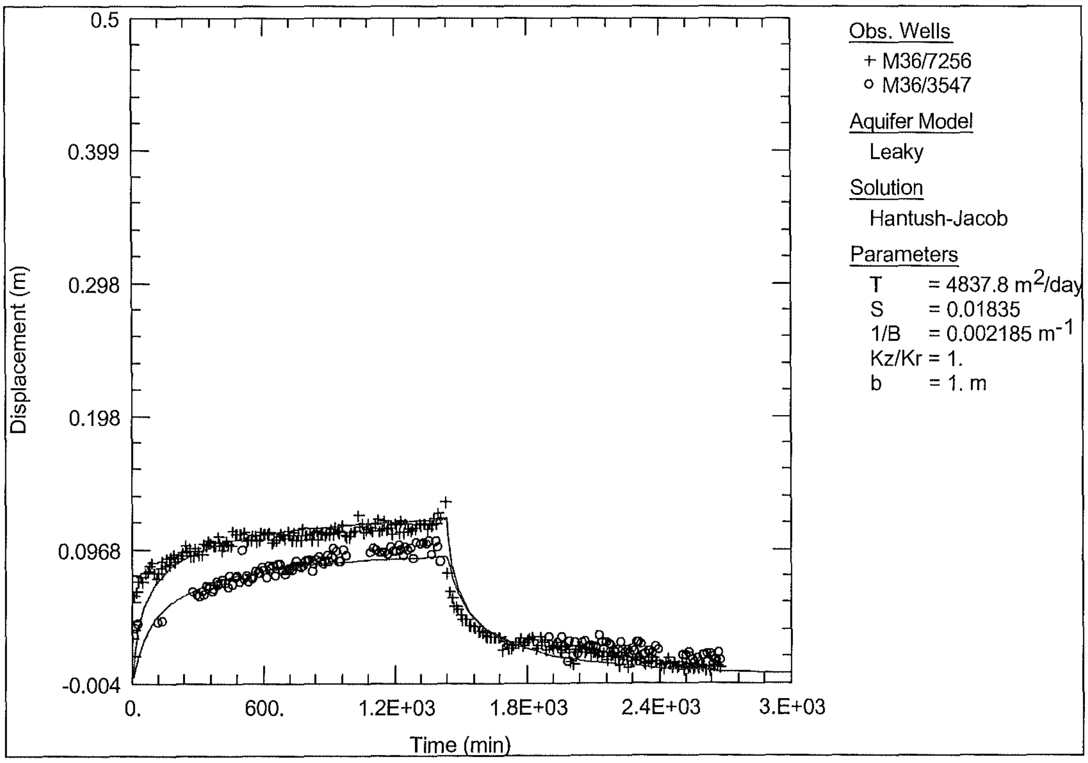




Note delayed yield response.

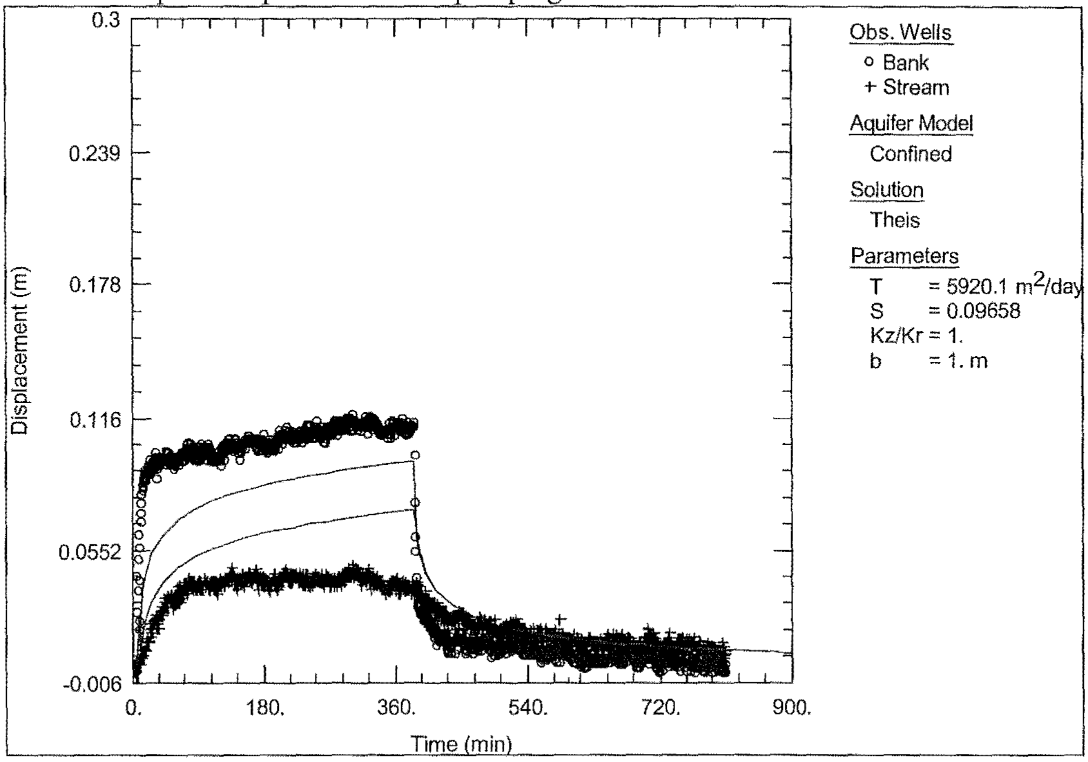
Aqtesolv analysis plots of:
Brookside aquifer response to 23 L/s pumping from M36/3548 October 2002

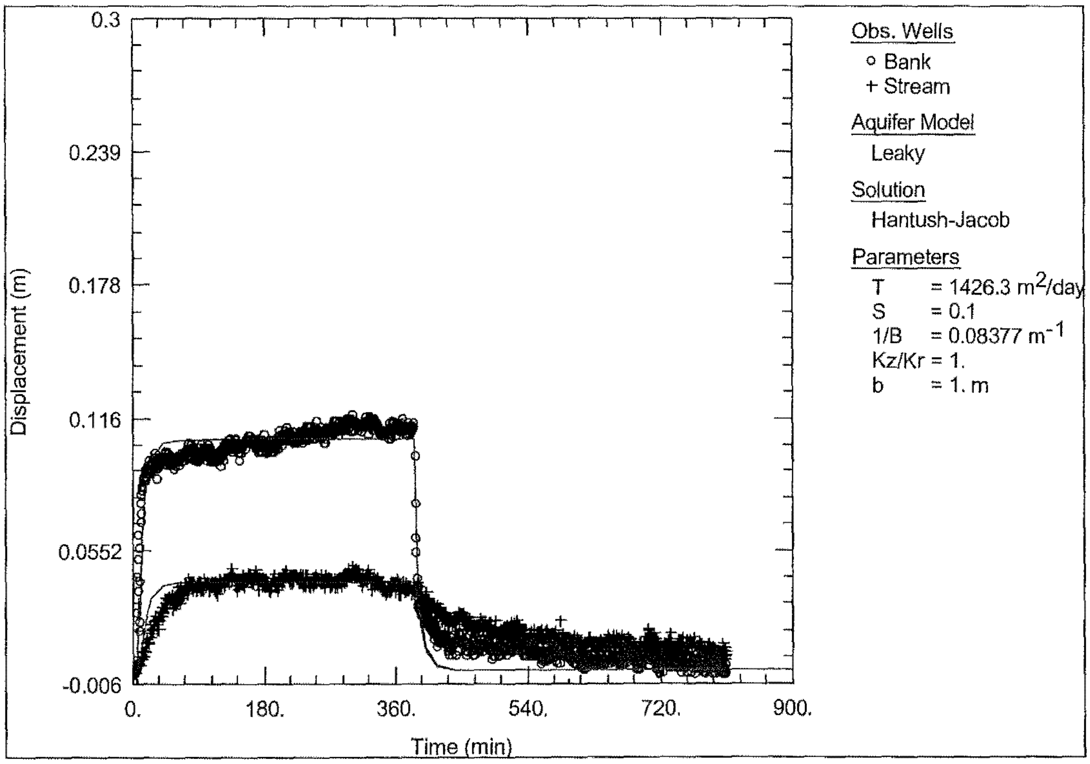




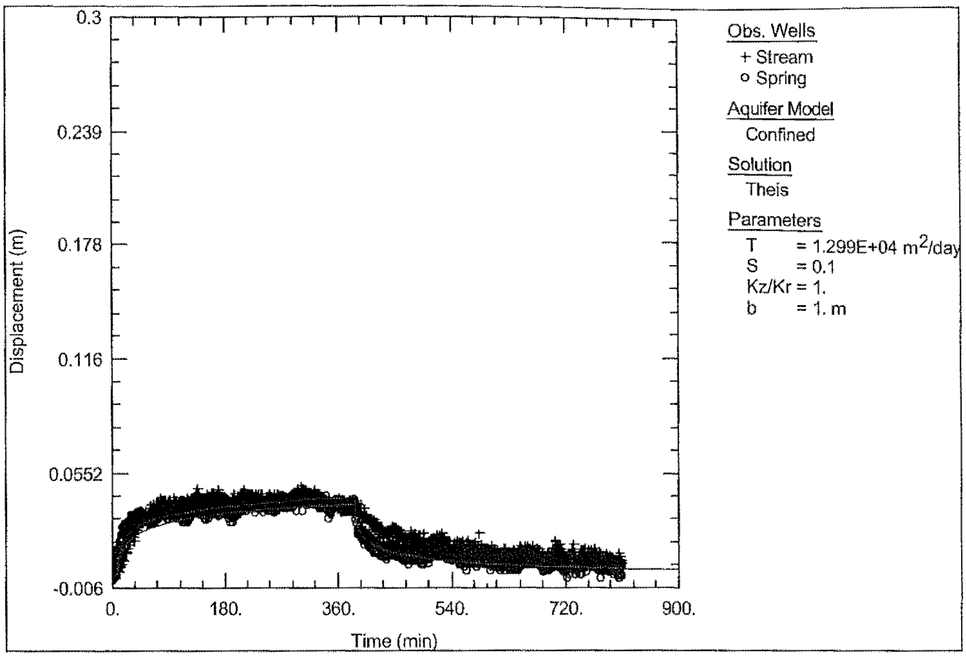
Again delayed yield response after a days pumping.

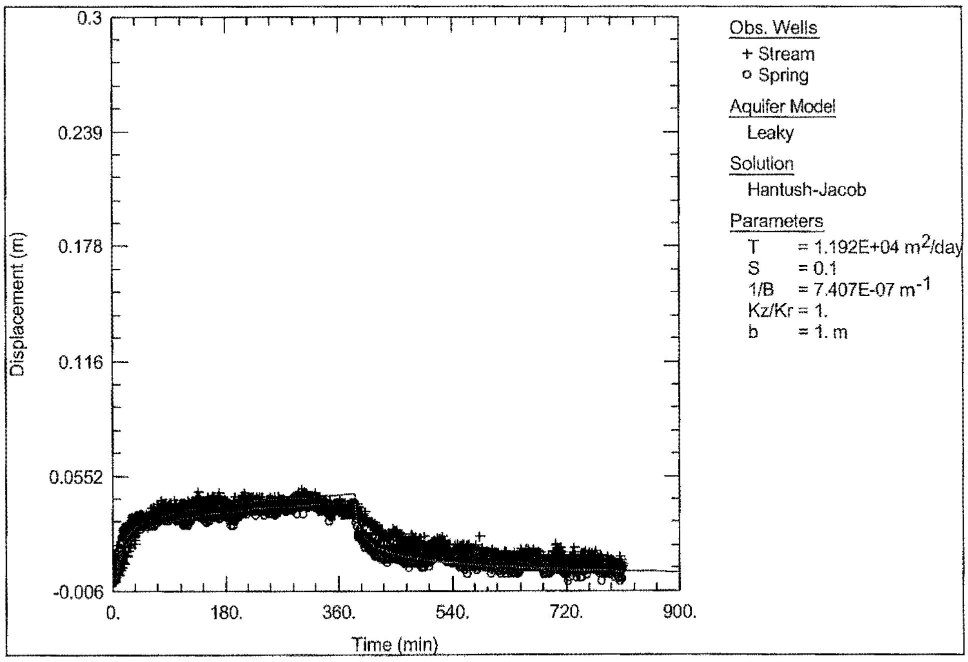
Aqtesolv analysis plots of:
Brookside aquifer response to 12 L/s pumping from M36/7256



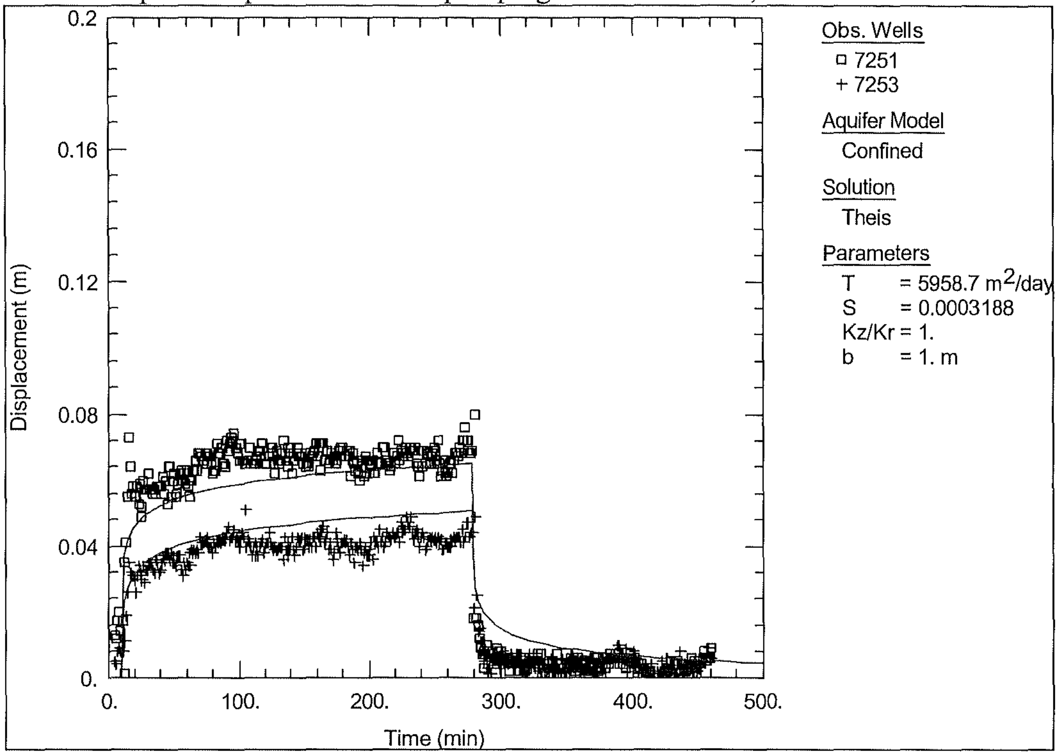


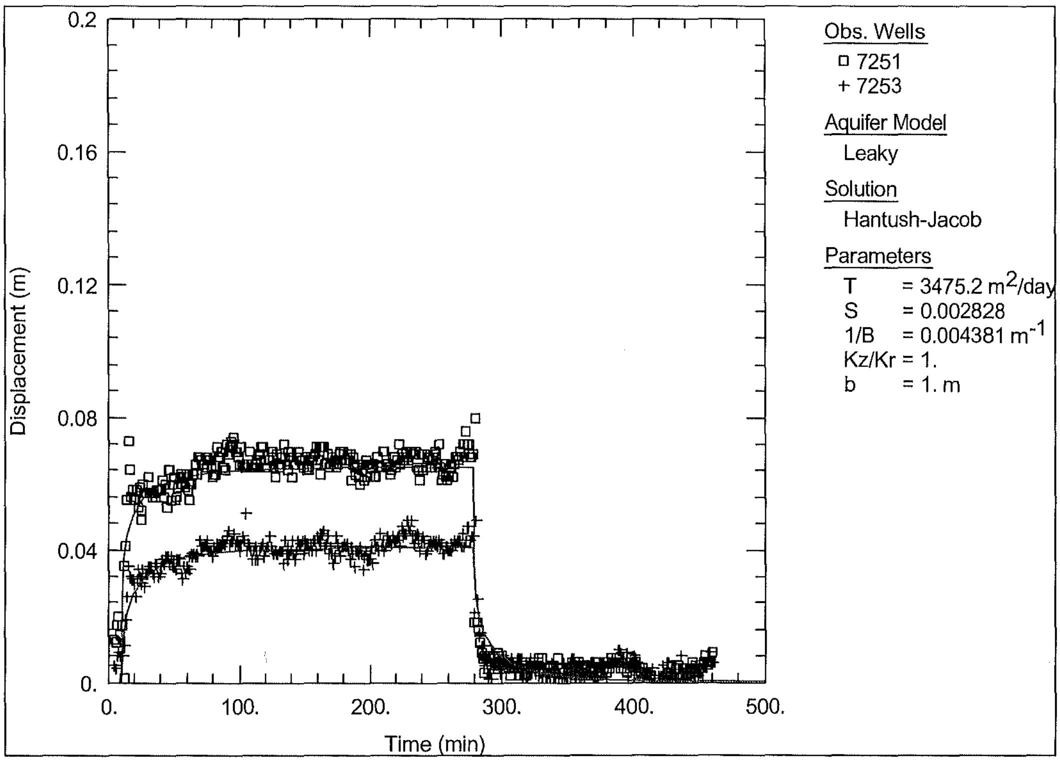
Aqtesolv analysis plots of:
Brookside aquifer response to 12 L/s pumping from M36/7256, using "in-stream" observation data





Aqtesolv analysis plots of:
Halswell aquifer response to 4.9 L/s pumping from M36/7252, 2002





Appendix N: Data Analysis